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# Rock Filters for Removal of Algae from Lagoon Effluents

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16. ABSTRACT

The objective of this project was to show that rock filtration was an effective, low cost unit process for removing algae from lagoon effluents and correspondingly upgrading lagoon treatment.

Sedimentation is the primary mechanism of algal removal within rock filter. The settling rates of three species of algae common to lagoons were measured as varying from 0.02 to 0.3 m/day, depending on species and temperature. Settling rates of algae from the Veneta, Oregon lagoon were about 0.05 m/day. A mathematical model of the sedimentation mechanism was constructed based on discrete settling theory. A linear relationship between TSS removal efficiency and hydraulic loading rate was demonstrated.

A full-scale horizontal flow operating rock filter designed for a maximum hydraulic loading of 0.28 $m^3/m^3$-day (1.6 days detention time) located at Veneta, Oregon was evaluated. Weekly average $BOD_5$ and TSS did not exceed 20 mg/l. With improved flow characteristics a pilot scale rock filter achieved similar results for a short period of testing at twice the hydraulic flow. During the one year of testing on the full-scale rock filter, the rate of decomposition of the sediment accumulating in the filter appeared to be low due to the limited D.O. available. Clogging, however, does not seem to be a major problem since sufficient void volume is available to store settled matter for a minimum of 20 years.

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# ROCK FILTERS FOR REMOVAL OF ALGAE FROM LAGOON EFFLUENTS

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## FOREWORD

The Environmental Protection Agency was created because of increasing public and government concern about the dangers of pollution to the health and welfare of the American people. The complexity of the environment and the interplay between its components require a concentrated and integrated attack on the problem.

Research and development is that necessary first step in problem solution and it involves defining the problem, measuring its impact, and searching for solutions. The Municipal Environmental Research Laboratory develops new and improved technology and systems for the prevention, treatment, and management of wastewater and solid and hazardous waste pollutant discharges from municipal and community sources, for the preservation and treatment of public drinking water supplies, and to minimize the adverse economic, social, health, and aesthetic effects of pollution. This publication is one of the products of that research, a most vital communications link between the researcher and the user community.

As part of these activities, this report was prepared to make available to the sanitary engineering community the results of a study on the upgrading of wastewater lagoon effluents for the removal of algae by the utilization of rock filters.

Francis T. Mayo
Director
Municipal Environmental Research
Laboratory

## ABSTRACT

Algae are beneficial to lagoon treatment in providing oxygen for aerobic stabilization; however, their presence in the effluent reduces the water quality achievable due to their contribution to both total suspended solids (TSS) and biochemical oxygen demand (BOD). Rock filtration was shown to be an effective, low cost unit process for removing algae from lagoon effluents and correspondingly upgrading lagoon treatment.

Sedimentation is the primary mechanism of algal removal within rock filters. The settling rates of three species of algae common to lagoons were measured as varying from 0.02 to 0.3 m/day, depending on species and temperature. Settling rates of algae from the Veneta, Oregon, lagoon were about 0.05 m/day.

A mathematical model of the sedimentation mechanism was constructed based on discrete settling theory. This model indicated that TSS removal efficiency was a function of $\theta/d_s$, where $\theta$ is the hydraulic retention time and $d_s$ is the effective settling distance. A linear relationship between TSS removal efficiency and hydraulic loading rate was demonstrated.

The performance of a full-scale operating rock filter located at Veneta, Oregon, was evaluated. This horizontal flow rock filter was designed for a maximum hydraulic loading of 0.28 $m^3/m^3$-day (detention time = 1.6 days). Weekly average effluent $BOD_5$ and TSS did not exceed 20 mg/l.

A pilot-scale rock filter operated at the Veneta lagoon achieved similar TSS removals at approximately twice the hydraulic loading. This discrepancy was apparently due to the improved flow distribution in the pilot-scale filter.

The settled algal matter in the rock filter is stored in the voids. Within the voids, rates of aerobic decomposition are probably small due to the limited dissolved oxygen available in the filter influent. However, the small amount of available dissolved oxygen probably will also limit anaerobic decomposition. As such, the algal mass in the voids does not degrade rapidly. Clogging does not appear to be a potentially serious problem since sufficient void volume is available to store settled matter for a minimum of 20 years.



This report was submitted in fulfillment of Grant Number R-805415 by Oregon State University under the sponsorship of the U.S. Environmental Protection Agency. This report covers a period from June 1, 1977 to March 31, 1978, and was completed as of May, 1978.

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## LIST OF ABBREVIATIONS AND SYMBOLS

### ABBREVIATIONS

| | |
|---|---|
| EPA | -- Environmental Protection Agency |
| $BOD_5$ | -- 5-day biochemical oxygen demand |
| TSS | -- total suspended solids |
| mg/l | -- milligrams per liter |
| $m^3/m^3$-day | -- cubic meters per cubic meter per day |
| gal/$ft^3$-day | -- gallons per cubic foot per day |
| cm | -- centimeter |
| ha | -- hectare |
| MGD | -- million gallons per day |
| $\mu$ | -- micrometers ($10^{-6}$ meters) |
| m/day | -- meters per day |
| mm | -- millimeters |
| m | -- meters |
| kg/ha-day | -- kilograms per hectare per day |
| lb/acre-day | -- pounds per acre per day |
| ft | -- feet |
| ml | -- milliliters |
| $m^3$/day | -- cubic meters per day |

### SYMBOLS

| | |
|---|---|
| $v$ | -- terminal settling velocity or sinking rate |
| $d_s$ | -- settling distance |
| $v_h$ | -- horizontal flow velocity |
| $L$ | -- basin length |
| $W$ | -- basin width |
| $v_c$ | -- critical settling velocity |
| $R$ | -- algal or suspended solids removal efficiency |
| $Q$ | -- flow rate |
| $p$ | -- porosity |
| $d_v$ | -- depth of void space |
| $d_r$ | -- depth of rock section |
| $\theta$ | -- detention time |
| $v_i$ | -- settling velocity of ith fraction of particles |
| $P(v_i)$ | -- fraction of particles with settling velocity $v_i$ |
| $P_c$ | -- fraction of particles with settling velocity greater than $v_c$ |
| $\bar{v}$ | -- mean settling velocity |
| $r$ | -- coefficient of correlation |
| $V$ | -- basin volume |

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# SECTION 1

# INTRODUCTION

## BACKGROUND

Aerobic stabilization lagoons are commonly employed by small municipalities and isolated industrial plants for wastewater treatment. Their popularity in these applications is due to relatively low construction costs and minimal operation and maintenance requirements. A major limitation of lagoons, however, is the presence of occasionally large quantities of algae in the effluent.

The Clean Water Act of 1972 (Public Law 92-500) required that all municipal effluents meet secondary treatment standards, defined by the EPA as a maximum of 30 mg/l of both 5-day biochemical oxygen demand ($BOD_5$) and total suspended solids (TSS) on a 30 consecutive day average basis. Compilation of data on lagoon treatment throughout the U.S., however, soon revealed that most lagoons could not meet a 30 mg/l TSS standard year-round because of the algal content of their effluents.

Consequently, a significant research effort was directed at finding effective methods for upgrading lagoon treatment, especially through the removal of algae. Middlebrooks, et al. (1) summarized the results of this research effort and compiled a list of fourteen possible techniques for upgrading lagoon treatment:

1. Centrifugation;
2. Microstraining;
3. Coagulation-Flocculation;
4. In-pond removal of particulate matter;
5. Complete containment;
6. Biological disks, baffles and raceways;
7. In-pond chemical precipitation of of suspended materials;
8. Autoflocculation;
9. Biological harvesting;
10. Oxidation ditches;
11. Land application;
12. Dissolved air flotation;
13. Granular media filtration; and
14. Intermittent sand filtration.

Successful application of lagoon upgrading techniques up to the mid-1970's, however, was generally limited to large scale treatment systems (7000 - 60,000 $m^3/d$) where technologically complex techniques such as chemical coagulation and flocculation, dissolved air flotation, and conversion to mechanical aeration could be successfully operated and maintained (2). Techniques that met the requirements of small communities for ease of operation, minimum maintenance and cost, and dependability of operation were generally not available or not fully developed.

As a result of this lack of adequate technology, the secondary treatment information regulations (40 CFR 133) were amended in 1977 to allow a case-by-case adjustment in the TSS standard for municipal wastewater treatment lagoons if the lagoon has a design capacity of 7570 $m^3$/day (2 MGD) or less, and lagoons are the sole process for secondary treatment. On November 15, 1978 the EPA published in the Federal Register (43 FR 53161) a list of suspended solids limitations for each state. These concentrations were based upon statistical analysis to reflect the concentration achievable 90 percent of the time and vary from 40 to 110 mg/l. This list serves as a guideline for the states in establishing TSS limitations for municipal lagoons.

Despite the recently relaxed Federal standards, the upgrading of lagoon treatment may be required in some areas where receiving water quality standards are stringent. Furthermore, national emphasis on continual improvements in water quality will eventually require reduced pollutional discharges from all sources, including municipal lagoons. The above considerations necessitate the development of dependable lagoon effluent polishing techniques which are compatible with lagoon treatment technology.

## ROCK FILTERS

An additional, promising alternative for the removal of algae from lagoon effluents is the rock filter. Very simply, a rock filter consists of a submerged bed of rocks (5 to 20 cm diameter) through which the lagoon effluent is passed vertically or horizontally, allowing the algae to become attached to the rock surface and thereby be removed. The basic simplicity of operation and maintenance are the key advantages of this process and make it especially attractive for application to small lagoons. The effluent quality achievable and the dependability of long-term operation, however, have not yet been proven.

### Previous Studies

Beginning in 1970, initial research into the rock filter was undertaken at the University of Kansas (3-7) from which O'Brien (8) concluded that:

1. Peak efficiency for submerged rock filters is achieved during the summer and early fall; this efficiency can produce an effluent meeting 30 mg/l $BOD_5$ - 30 mg/l TSS discharge standards at a design of 1.6 $m^3/m^3$-day (12 gal/$ft^3$-day). During the winter and spring, the efficiency of suspended solids removal decreases significantly, and a maximum design loading of 1.2 $m^3/m^3$-day (9 gal/$ft^3$-day) is recommended.

2. The filters may be anaerobic during the summer and early fall and will produce hydrogen sulfide if sulfates are present.

3. The rate of solids accumulation in submerged rock filters should allow an effective filter life of greater than 20 years.

4. Rock sizes should be greater than 2.5 cm and less than 12.7 cm.

O'Brien did not elaborate on the basic mechanism of algal removal in rock filters, nor the possible effluent quality which could be achieved at lower loading rates than those used of 0.40 to 2.7 $m^3/m^3$-day (3-20 $gpd/ft^3$).

## The Veneta Rock Filter

A full-scale rock filter was designed and constructed as part of a lagoon expansion and upgrading project at Veneta, Oregon in 1975. The rock filter was conservatively designed to meet 30 mg/l $BOD_5$ and TSS limitations in accordance with Federal regulations applicable at that time.

A schematic flow diagram of the Veneta, Oregon wastewater treatment system is shown in Figure 1. The system treats wastewater from a sewered population of approximately 1400 with no industrial wastewater contribution. Raw wastewater is pumped into the larger first cell and flows through the smaller second cell by gravity. Both lagoons are designed for a minimum water elevation of 0.76 m (2.5 ft) and a maximum of 1.83 m (6.0 ft). The present organic loading on the lagoon is 17.8 kg $BOD_5$/ha-day (15.9 lb/acre-day) and the average detention time is 51 days. Lagoon effluent is pumped to the rock filter by a submersible pump with a maximum capacity of approximately 2180 $m^3$/day (400 gpm).

A plan and cross-section of the rock filter is shown in Figure 2. The pressure pipe carrying lagoon effluent discharges into a 0.3 m (1.0 ft) square influent channel upon entering the rock filter. The lagoon effluent rises from the influent channel and moves horizontally towards the discharge weirs where it flows into a covered effluent channel. Finally, the flow from each side of the rock filter is combined, chlorinated, and discharged to the nearby Long Tom River.

The rock surface is approximately 0.30 m (1.0 ft) above the water elevation to prevent growth of algae on the rock filter. The effective surface area of the rock filter is 5400 $m^2$ (58,000 $ft^2$) and the effective volume is 8,200 $m^3$ (290,000 $ft^3$). The in situ average porosity of the 7.6 to 15.2 cm (3 to 6 in) rock bed was measured as 42 percent.

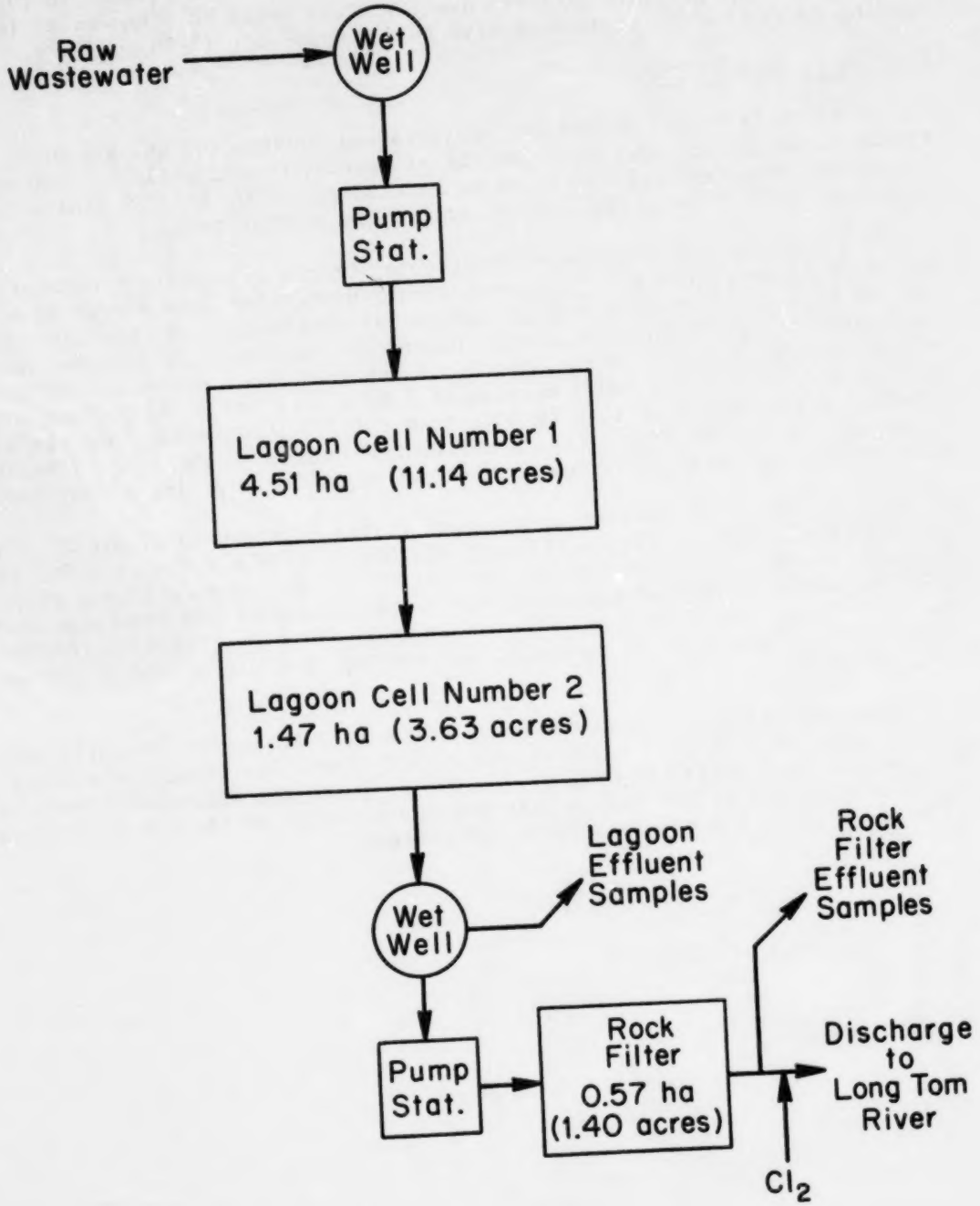


Figure 1. Schematic flow diagram of the wastewater treatment system at Veneta, OR.

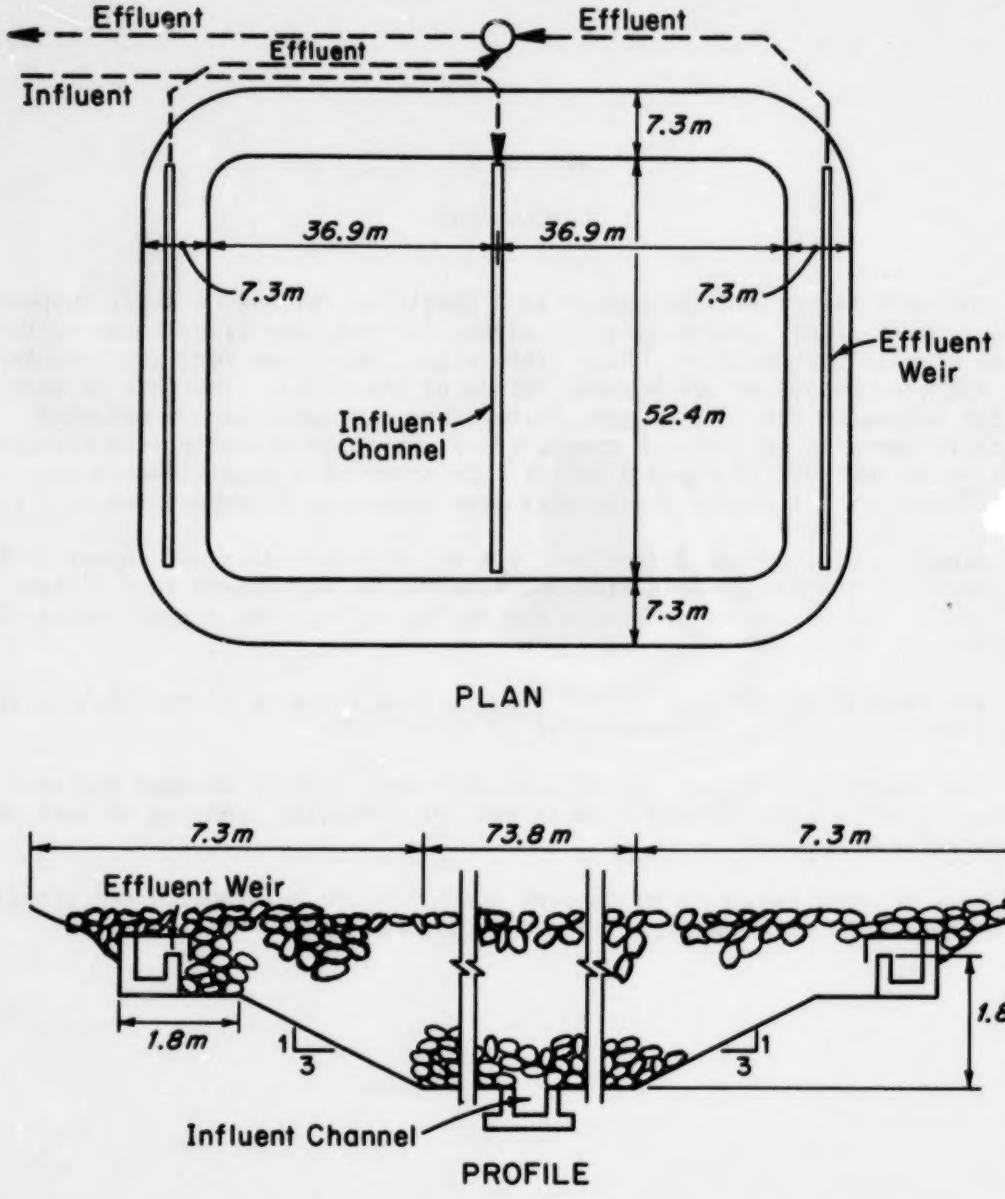


Figure 2. Veneta rock filter plan and profile.

## SECTION 2

## CONCLUSIONS

The rock filter acts primarily as a clarifier for lagoon algal suspended solids. Most algae, including green algae, diatoms, and flagellates settle to the nearest rock surface. Blue green algae, which can form gas vacuoles, rise and are trapped on the bottom surface of the rocks. The fate of most settled solids in the rock filter is long-term storage. Lagoon effluent typically contains only enough dissolved oxygen to aerobically stabilize a fraction of the settled organic matter. Environmental conditions in the rock filter are not conductive to extensive anaerobic decomposition.

Plugging of the rock filter bed by settled matter does not appear to be a problem for the design rock size and loadings of the Veneta rock filter. Sufficient void volume is available for storage of settled organic matter for a minimum of 20 years.

BOD removal in the rock filter results from settling of particulate BOD with little net removal or generation of soluble BOD.

The Veneta rock filter can consistently meet a daily maximum effluent limitation of 20 mg/l TSS and 20 mg/l BOD for hydraulic loadings of less than 0.30 $m^3/m^3$-day.

Rock filters require a minimum of operation and maintenance and appear to be compatible with the capabilities of typical lagoon operations.

## SECTION 3

## RECOMMENDATIONS

The settling rate of algae is the controlling factor in the design of rock filters. As such, settling rates should be determined for typical species and combinations of species found in wastewater lagoons. This information would allow rational engineering design based on known algal combinations at a particular location.

The operational characteristics of rock filters under severe cold climatic conditions is unknown. A monitoring study should be undertaken for a facility where icing of the lagoon and rock filter would be encountered during winter months.

## SECTION 4

## RESEARCH PLAN

### REMOVAL MECHANISM

Previous research on rock filters did not fully identify the basic algal removal mechanism or the significant environmental factors affecting performance of rock filters. Consequently, the first step in this project was to hypothesize what the basic algal removal mechanism was and to develop a mathematical model of this mechanism so that field results could be compared to a theoretical framework. A review of the literature suggested that sedimentation was the primary algal removal mechanism for several reasons. First, it was considered unlikely that true filtration could be a major mechanism due to the large pore size within rock filters. Second, it did not appear that simple impingement of algal particles upon the rocks and subsequent attachment could be an effective removal mechanism without a difference in specific gravity between the liquid and particle due to the very slow, laminar horizontal flow velocities (less than 1.0 m/day). Third, the importance of algal settling to both marine and freshwater phytoplankton ecology has been recently recognized (8,9,10) and would appear to be important for the physical dimensions of the rock filter.

### OBJECTIVES

The objectives of this project were:

1. To confirm that sedimentation is the primary removal mechanism operating within rock filters,

2. To determine typical settling velocities of various algal species that are common in lagoon effluents,

3. To evaluate the present operating characteristics of the rock filter at Veneta, Oregon for removing algae from lagoon effluents,

4. To estimate the long-term operating characteristics of a rock filter after considerable algal material has collected in the porous media, and

5. To determine engineering design criteria for rock filters that would optimize algal removal rates.

## APPROACH

To fulfill the objectives described above, the project was divided into three focuses of effort:

1. Measurement of settling velocities for pure cultures of typical lagoon algal species,

2. Sampling and analysis of influent and effluent samples and physical observation of the Veneta rock filter to determine its operational performance, and

3. Construction, operation, and evaluation of a pilot-scale rock filter and comparison of its performance with that of the full-scale system at Veneta, Oregon.

A description of the experimental methods and results associated with each of the above-described three phases are contained in Sections 7, 8 and 9, respectively.

## SECTION 5

## CHARACTERIZATION OF LAGOON ALGAE

Algae perform two primary functions within aerobic stabilization lagoons. First, they release oxygen into the water due to their photosynthetic activity, and this oxygen then is available to aerobic bacteria for decomposition of organic material. Second, they absorb and assimilate nutrients (ammonia, nitrates, phosphates) produced by aerobic decomposition of organic wastes. While generally advantageous within the lagoon treatment process, these algae constitute the major source of $BOD_5$ and suspended solids in lagoon effluents and limit the effluent quality achievable by lagoon treatment.

Lagoons typically contain a very heterogeneous, mixed culture of algae. Additionally, this culture may change rapidly in response to changing environmental conditions. An understanding of the principles behind the successful removal of algae from lagoon effluents by upgrading techniques can only be achieved with a basic knowledge of the physical, chemical, and biological properties of the species occurring within lagoons. To this end, this section presents a generalized classification scheme for algae. This classification scheme emphasizes settling behavior and/or motility factors that are directly related to the proposed sedimentation mechanism for rock filters. Also, the abundance of the various classes of algae within lagoons is discussed.

### CLASSIFICATION

Practically all the algae common to lagoons tend to be planktonic, that is, they remain dispersed in the water column rather than attached to a surface. A simplified classification of planktonic algae into four basic groups is often used in the field of environmental biology and is appropriate for lagoon studies (11). These groups are blue-green algae, diatoms, flagellate algae, and green algae. Typical examples of genera representative of the four groups found in stabilization ponds are: green algae - Chlorella, Scenedesmus, Ankistrodesmus; blue-green algae - Anacystis (Microcystis), Oscillatoria; flagellate algae - Chlamydomonas, Euglena; and diatoms - Nitzschia, Cyclotella.

It should be noted that some algae within the taxonomic classification for green algae (Chlorophycae) have flagella for motility (for example, Chlamydomonas). Within the above classification scheme, however, these algae would be classified as flagellates, not green algae.

### ABUNDANCE

A large scale study of algae from lagoons in the U.S. and nearby territories was conducted by Palmer (11). This study covered 74 ponds, involved 929 sampling sites and lasted more than six years. Of the 125 genera identi-

fied in lagoons, approximately 50 percent were green algae, 25 percent were pigmented flagellates, 15 percent were blue-green algae, and 10 percent were diatoms. An index of abundance was developed by Palmer to describe the frequency and extent of occurrence of each algal genera (Table 1). This table shows that the majority of the 25 most abundant algal genera are green algae, flagellates are second most abundant, while blue-green and diatoms are much smaller in abundance.

## MOTILITY AND SETTLING BEHAVIOR

Planktonic algae must have some special mechanism or adaptation to remain in the photic zone, for protoplasm, skeletons, and cell walls are heavier than water. This mechanism may be active, allowing direct control of depth, or it may be passive, involving a reduction in sinking rate so that turbulence will cause resuspension. Active mechanisms include use of flagella for motility (flagellate algae) and formation of gas vacuoles (most blue-green algae) for buoyancy. Identified passive mechanisms include:

1. Maintenance of a young culture through rapid growth (e.g., as organisms age or become nutrient deficient their sinking rate increases),
2. Reduction in cell size through division (e.g., increased surface area to volume ratio increases frictional resistance to settling), and
3. Incorporation of spines or bristles in cell walls which increase fluid drag.

Additionally, the existence of other passive mechanisms has been hypothesized including:

1. Accumulation of fatty food reserves or oil,
2. Accumulation of abundant mucilage, and
3. Selective accumulation of ions.

Algae within the four classes described previously utilize different mechanisms for regulating sinking rate.

### Green Algae and Diatoms

Green algae and diatoms are nonmotile, depend upon wind-induced or thermal circulation to maintain themselves in the photic zone, and will settle under quiescent conditions (12). Passive mechanisms are utilized to retard settling, however, and a significant amount of research has been conducted to describe their settling behavior as a function of physiological and environmental conditions. Most of this research has been conducted on diatoms, particularly marine diatoms.

Using a settling chamber and an inverted microscope, Smayda and Boleyn

TABLE 1. ALGAE MOST ABUNDANT AND WIDESPREAD IN WASTEWATER PONDS (AFTER PALMER (11))

| Rank | Genus | Classification[1] | Score[2] |
|---|---|---|---|
| 1 | Chlorella | G | 51 |
| 2 | Ankistrodesmus | G | 49 |
| 3 | Scenedesmus | G | 49 |
| 4 | Euglena | F | 48 |
| 5 | Chlamydomonas | F | 47 |
| 6 | Oscillatoria | BG | 46 |
| 7 | Micractinium | G | 39 |
| 8 | Golenkinia | G | 37 |
| 9 | Anacystis | BG | 34 |
| 10 | Oocystis | G | 34 |
| 11 | Chodatella | G | 33 |
| 12 | Nitzchia | D | 32 |
| 13 | Nannochloris | G | 31 |
| 14 | Planktosphaeria | G | 29 |
| 15 | Pandorina | F | 29 |
| 16 | Pteromonas | F | 28 |
| 17 | Closteridium | G | 28 |
| 18 | Cryptomonas | F | 28 |
| 19 | Chlorococcum | G | 28 |
| 20 | Schizothrix | BG | 28 |
| 21 | Cyclotella | D | 27 |
| 22 | Phacus | F | 27 |
| 23 | Schroederia | G | 25 |
| 24 | Trachelomonas | F | 25 |
| 25 | Actinastrum | G | 25 |

[1] G = Green algae
F = Flagellate
BG = Blue-green
D = Diatom

[2] Score was determined by adding together the highest sampling date abundance figure, the number of states for the genus, and the number of states where abundance figure was 5 or above. Genera with similar scores were ranked according to the first item.

(13) measured the sinking rate of several marine diatoms as summarized in Table 2. Smayda (14) reported that the mean settling rate of the freshwater diatom Asterionella formosa progressively increased from 0.26 to 0.62 m/day over a 22-day growth period. Heat or algicide-killed cells settled more rapidly than live cells, indicating a loss of phytoplankton suspension mechanisms with cell death.

Titman and Kilham (15) developed a sensitive fluorometric technique (16) to investigate the sinking rate of freshwater phytoplankton, including one green species (Scenesdesmus quadricauda) and three diatoms, in both exponential and stationary growth phases (Table 3). Settling rate for cells in nutrient limited and nutrient unlimited conditions were also investigated. It was concluded that the higher settling rates of stationary phase cells were an apparent response to limited nutrient conditions.

Based on sinking rate measurements with marine diatoms, Eppley, et al. (9) concluded that sinking rate is not a species specific constant, but is dependent on cell nutrient status, cell diameter, cell aggregation, and compostion of the culture media. It was hypothesized that cells of a given species may exist in up to three distinct physiological states with respect to buoyancy: neutral buoyancy, a moderate sinking rate state, and a high sinking rate state, with rapid transition to higher sinking rate states occurring with declining physiological activity.

## Flagellate Algae

Little research has been conducted concerning the use of flagellate motility by algae as a function of environmental or physiological conditions. Velocities achievable through the use of flagella (up to 2 meters per hour is reported (12)) are more than sufficient to overcome settling tendencies. Apparently, however, these algae depend on light for directional orientation in the use of their motility and will settle in darkness (9).

Eppley, et al. (9) measured the sinking rates of cultures of marine flagellates in the absence of light (Table 4). Sinking rates appeared to increase with cell diameter and were similar to those for unicellular diatoms of similar size. The increased sinking rate of non-growing cultures of Gonyaular polyedra was interpreted as resulting from cessation of growth rather than loss of motility.

## Blue-Green Algae

Blue-green algae generally contain gas vacuoles for buoyancy regulation. Although the mechanism regulating formation of gas vacuoles is not entirely clear, gas vacuoles develop most abundantly (causing flotation) in dim light and collapse as a result of photosynthesis, often resulting in a diurnal up-and-down movement. Also, higher concentrations of nutrients favor gas vacuole formation (17). The formation of mats by certain blue-green algae, such as Anacystis (Microcystis), is evidence of effective use of gas vacuoles.

Titman and Kilham (15) measured the mean rising rate of the blue-green algae Spirulina platensis as 0.45 m/day using a modified fluorometric technique.

TABLE 2. MEAN SINKING RATES OF DIATOMS (AFTER SMAYDA AND BOLEYN (13))

| Genus | Sinking Rate (m/day) | | | |
|---|---|---|---|---|
| | Minimum | Young Cells | Old Cells | Maximum |
| Thalassiosira | 0.05 | 0.1 | 0.28 | 45 |
| Nitzschia | 0.2 | 0.26 | 0.5 | 3 |
| Skeletonema | 0.2 | 0.3 | 1.4 | 7 |
| Rhizosolenia | 0.05 | 0.2 | 1.8 | 23 |

TABLE 3. COMPARISON OF MEAN SINKING RATES FOR FOUR SPECIES OF FRESHWATER PHYTOPLANKTON (AFTER TITMAN AND KILHAM (15))

| Species | Cell Radius (μ) | Sinking Rate (m/day) | | Ratio (Stationary/ Exponential) |
|---|---|---|---|---|
| | | Exponential Growth Phase | Stationary Growth Phase | |
| Cyclotella meneghiniana | 1.0 | 0.08 | 0.24 | 3.0 |
| Scenesdesmus quadricauda | 4.2 | 0.27 | 0.89 | 3.3 |
| Asterionella formosa | 12.5 | 0.20 | 1.48 | 7.4 |
| Melosira agassizii | 27.4 | 0.67 | 1.87 | 2.8 |

TABLE 4. SINKING RATES OF MARINE FLAGELLATES (AFTER EPPLEY, ET AL. (9))

| Species | Cell Dimensions* (μ) | Sinking Rate (m/day) | |
|---|---|---|---|
| | | Growing Cultures | Non-Growing Cultures |
| Monochrysis lutheril | 5.9 | 0.18 | - |
| Dunaliella tertiolecta | 6x9.5 | 0.39 | - |
| Cricosphaera elongata | 14x16 | 0.25 | - |
| Gonyaulax polyedra | 47 | 2.8 | 6.0 |
| Coccolithus huxleyi | | | |
| with coccoliths | 6.5 | 1.3 | - |
| coccoliths removed | 5.2 | 0.28 | - |
| Cricosphaera carterae | 17 | - | 1.7 |

*Given as average diameter for spherical cells or average diameter and average cell length for other cells.

## SECTION 6

## MATHEMATICAL MODEL OF ROCK FILTER SETTLING

### INTRODUCTION

As described in the previous section, species of the green algae class are most commonly dominant within lagoons. While these algae utilize passive mechanisms to retard settling, they will settle under quiescent conditions. Diatoms, while infrequently dominant in lagoons, will settle at similar rates. Flagellate algae, the second most abundant class, will settle under dark conditions and, due to their generally larger size, at rates equal to or greater than those of green algae. The settling rates involved are often very small (less than one meter per day), but are measurable by sensitive fluorometric techniques.

Rock filters provide the dark, quiescent environment and small settling distance necessary to remove these algae by sedimentation. This section presents a mathematical model of this settling mechanism based on discrete settling theory.

### THE MODEL

Settleable algal particles obviously will follow a tortuous path through the heterogeneous rock filter bed before finally settling upon a rock surface. Developing an effective and usable model of rock filter sedimentation characteristics requires that the major variables such as rock size, void volume, and configuration be considered, while assuming a more homogeneous basin and a more straightforward settling path. For a horizontal flow rock filter, such as the one located at Veneta, Oregon, a simplified settling model can be applied as shown in Figure 3. Within this model, the rocks are envisioned as comprising a series of horizontal plates, of thickness $d_r$, that divide the total depth of the rock filter into alternate sections of rock and void space. The depth of each void section is $d_s$ and corresponds to the maximum distance that an individual algal particle must settle to be removed from the flow stream and become part of the attached slime layer on the rocks. The length L and width W of the horizontal plates in the conceptual model corresponds to the actual length and width of the rock filter basin.

In accordance with simple discrete settling theory, an algal particle entering the rock filter at the top of one of the settling chambers must settle a distance $d_s$ before it travels L horizontally in order to be removed. That is, for complete removal:

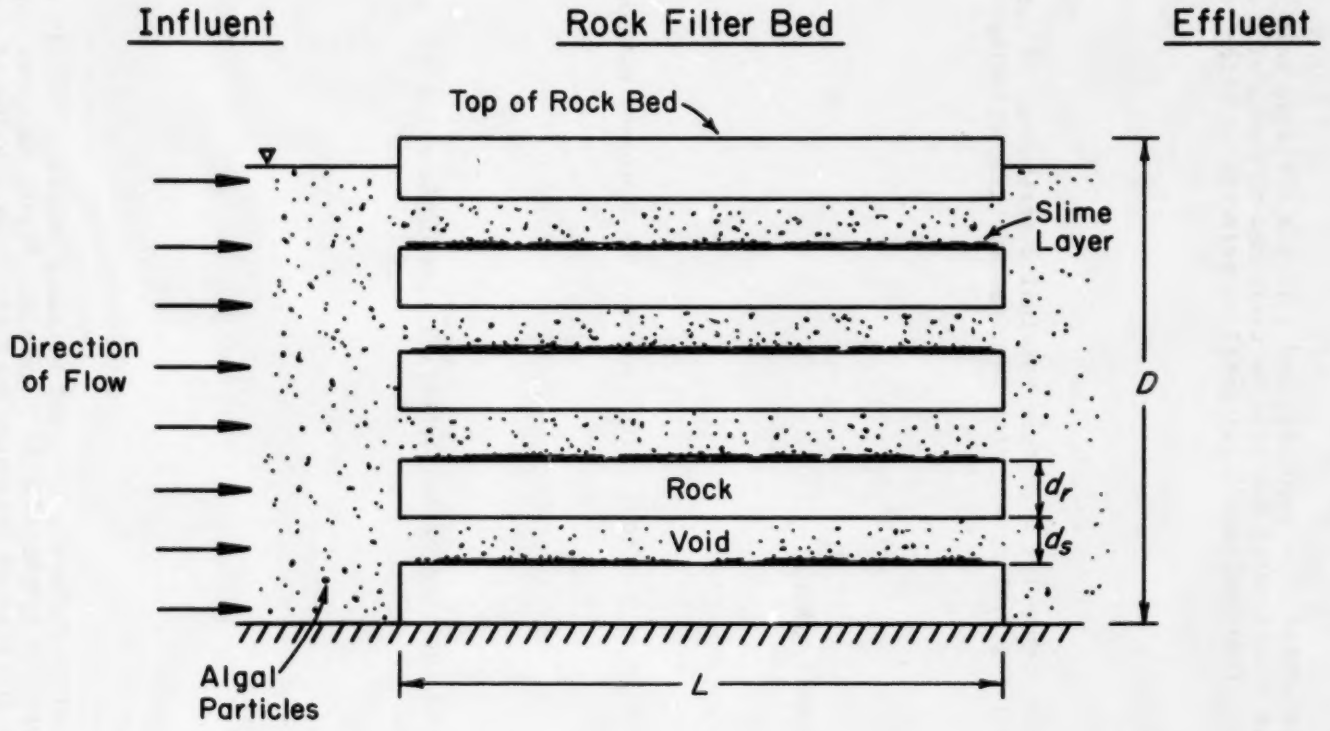


Figure 3. Rock filter settling conceptual model.

$$\frac{v}{d_s} > \frac{v_h}{L} , \qquad (1)$$

where $v_h$ is the horizontal flow velocity, and v is the settling velocity of the particle. This relationship can also be expressed in terms of a critical settling velocity $v_c$ (the smallest algal settling velocity at which complete removal occurs):

$$v_c = \frac{d_s v_h}{L} . \qquad (2)$$

The removal efficiency for a uniform vertical distribution of particles approaching the settling plates, all with the same settling velocity v, can be expressed as:

$$R = \frac{vL}{d_s v_h} . \qquad (v \leq v_c) \qquad (3)$$

If plug flow is assumed, then:

$$v_h = \frac{Q}{WDp} , \qquad (4)$$

where p is the porosity of the rock filter and can be expressed within the conceptual model as:

$$p = \frac{d_r}{d_s + d_r} . \qquad (5)$$

Since Vp/Q represents the theoretical detention time $\theta$, Equation (1) can be rewritten as:

$$v_c = \frac{d_s}{\theta} , \qquad (6)$$

and Equation (3) as:

$$R = \frac{v\theta}{d_s} . \qquad (v \leq v_c) \qquad (7)$$

Equation (7), which assumes a constant settling velocity for all algal particles, is represented graphically in Figure 4. Figure 4a shows removal efficiency (R) as a function of detention time ($\theta$). For a value of $\theta$ greater than or equal to $d_s/v$, the removal efficiency is 100 percent as suggested by Equation (7). Another useful method for plotting removal efficiency is shown

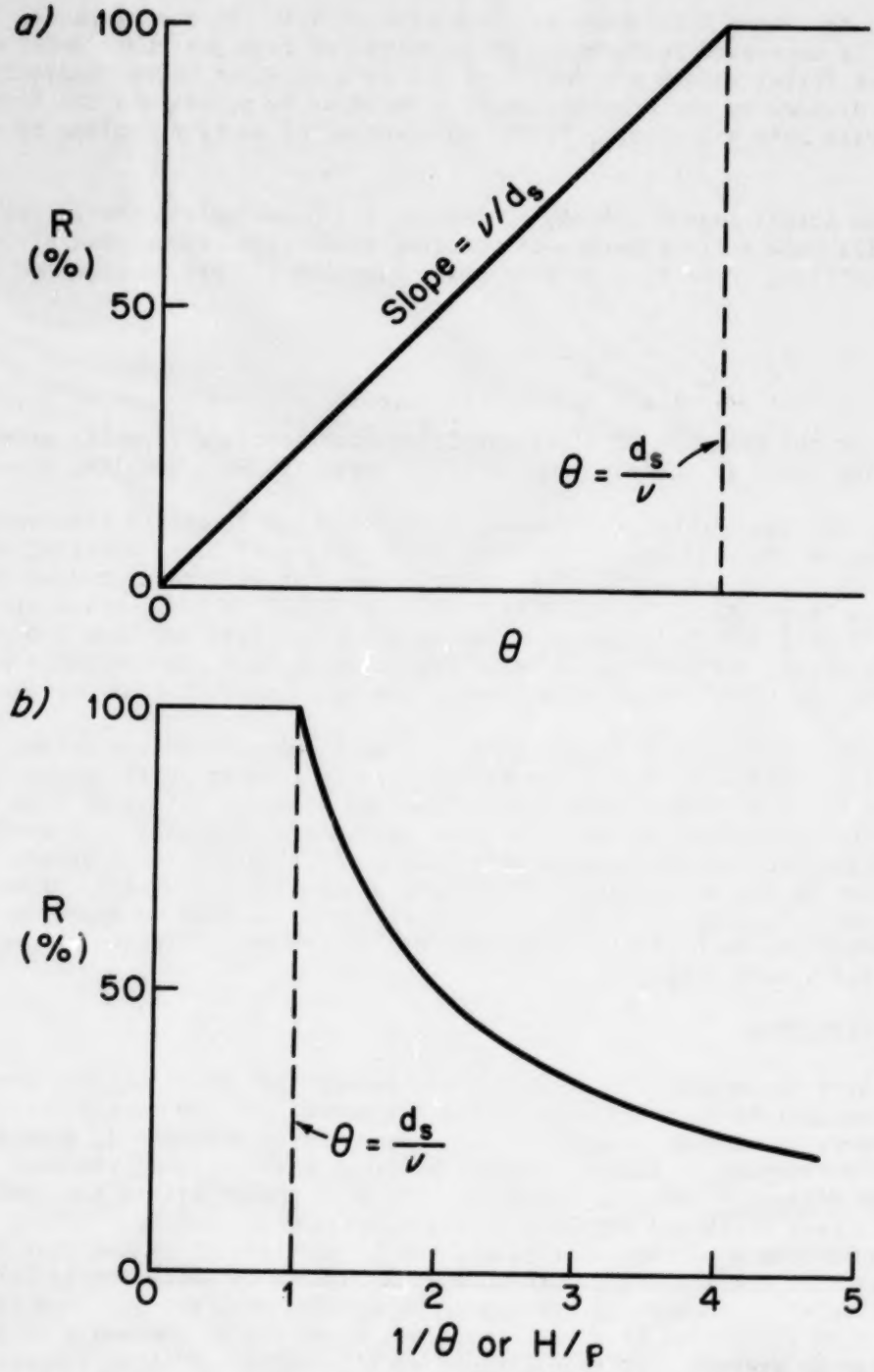


Figure 4. Removal efficiency vs. detention time for algal culture with uniform settling velocity, v.

in Figure 4b, where R is shown as a function of $1/\theta$. If the hydraulic loading rate (H) is expressed in terms of cubic meters of flow per cubic meter of total rock filter volume per day, then $1/\theta$ is equivalent to the hydraulic loading rate divided by the porosity (H/p). Dividing by p converts the hydraulic loading rate into a loading rate per unit volume of settling volume or void space.

In an actual lagoon system, of course, the planktonic algae in the effluent will have a distribution of settling velocities rather than a single, uniform settling velocity. In this case, Equation (7) can be expanded to:

$$R = P_c + \frac{\theta}{d_s} \sum_{v_i=0}^{v_c} v_i \cdot P(v_i), \qquad (8)$$

where $P_c$ is the fraction of algal particles with settling velocity greater than $v_c$ and $P(v_i)$ is the fraction of algal particles with settling velocity $v_i$.

The relationship between removal efficiency and detention time resulting from Equation (8) will depend upon the distribution of algal settling velocities in the rock filter influent. This relationship can be illustrated by considering a hypothetical normal distribution of algal settling velocities as shown in Figure 5. It is not known whether lagoon algal cultures typically exhibit a normal distribution of settling velocity, but the available data on algal settling rates indicates that this may be a reasonable assumption (16).

Figure 6 shows removal efficiency (R) as a function of the detention time ($\theta$) and its inverse ($1/\theta$) for the normal distribution of settling velocities in Figure 5. R is typically a linear function of $\theta$ for values of R up to or greater than 50 percent where it becomes nonlinear. The plot of R versus $1/\theta$ in Figure 6b shows an approximate linear relationship for R values between about 60 and 90 percent. Therefore, plots of R versus $1/\theta$ (or versus the hydraulic loading rate) may be the most useful in that an approximate linear relationship may be established for the higher removal efficiencies usually desired for a rock filter.

## MODEL APPLICATION

As with any model, the discrepancies between the model and the real physical system must be examined in applying the model. In the rock filter settling model, it must be recognized that the settling distance $d_s$ does not directly correspond to any physically measurable property of the rock bed, but is an effective settling distance. The void spaces within the rock filter are of varying depth and settling of algae takes place not by a gradual approach towards a horizontal surface, but by statistical chance that the algal particle comes close enough to a rock surface to settle on it before the horizontal flow velocity carries it beyond the rock's edge. Due to reduced flow velocities near rock surfaces, algae may be removed more effectively than an average settling distance would suggest. With this understanding of an effective settling distance, however, the model can be applied to describe rock filter performance.

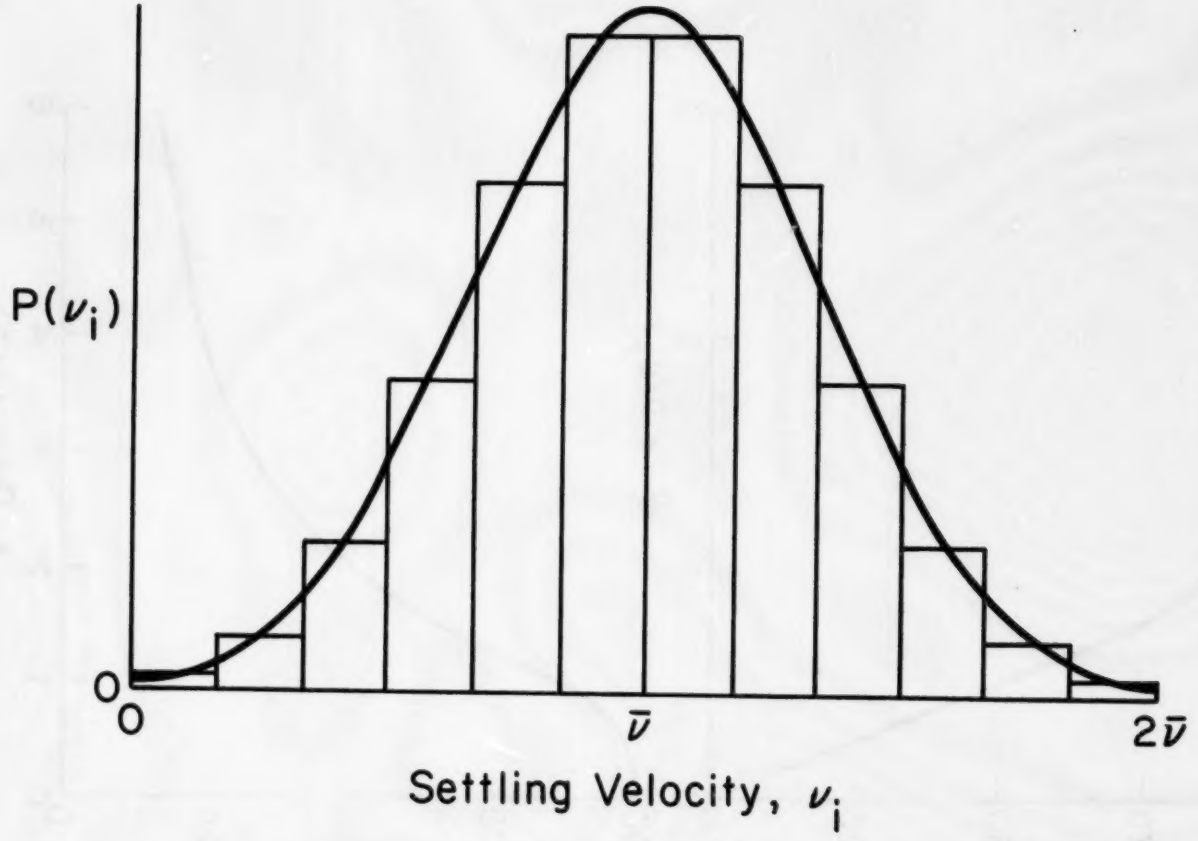


Figure 5. Hypothetical normal distribution of settling velocities.

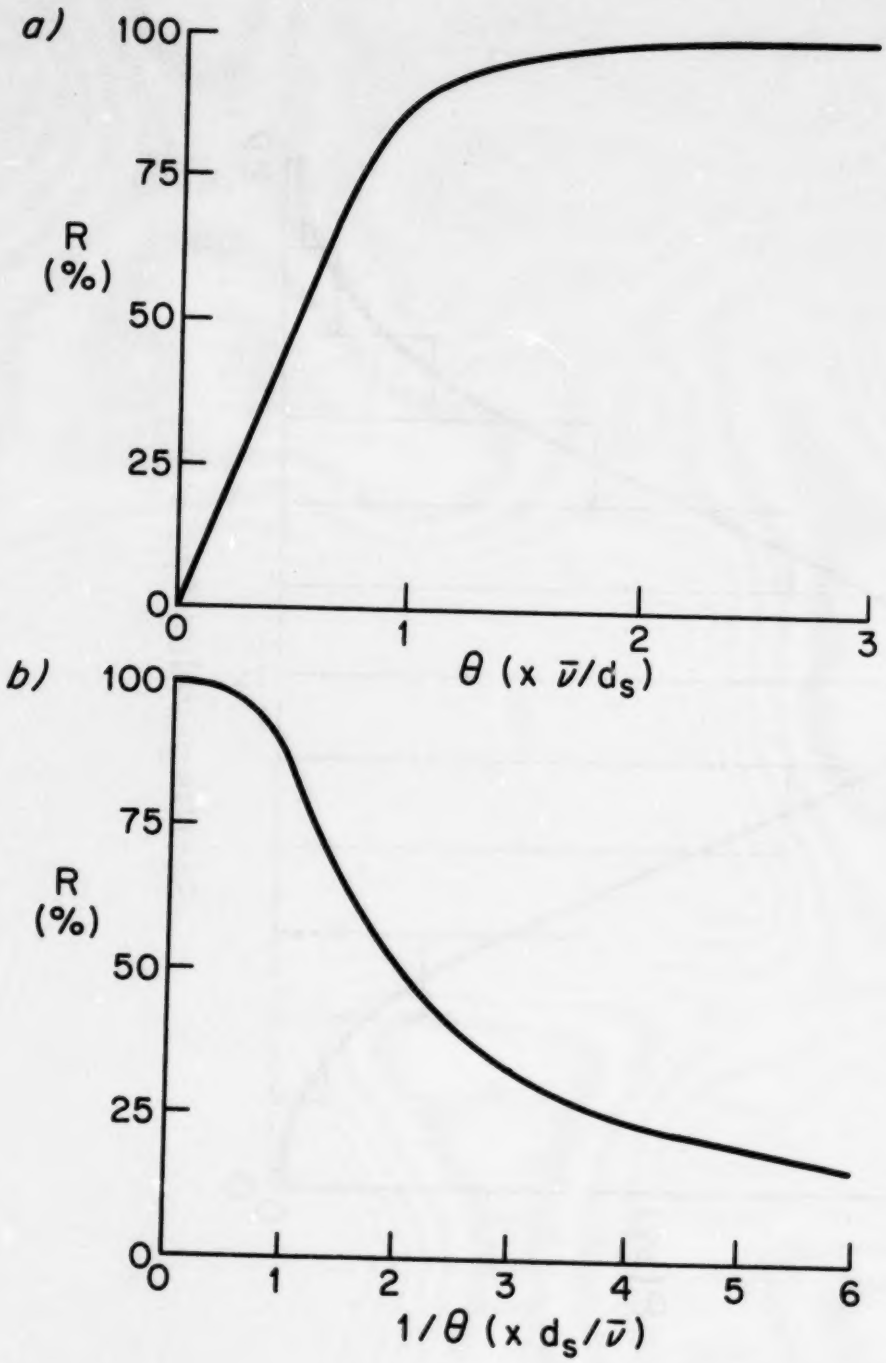


Figure 6. Removal efficiency vs. detention time for normal distribution of settling velocities.

An additional problem not heretofore mentioned is the ability of blue-green algae to rise by gas vacuole formation. Evidence discussed in the previous section indicates that in the dark, nutrient-rich environment of the rock filter, gas vacuole formation would occur, resulting in flotation of blue-green species. In both the model and the rock filter system, however, it is easy to demonstrate that flotation is only a minor variation of the proposed settling mechanism. Within the model, the same equations apply except that v corresponds to a rising velocity rather than a sinking velocity. Within the rock filter, rising blue-green algae would be trapped on the bottom surface of the rocks rather than the top. The behavior of blue-green algae in the Veneta rock filter and in settling tests during this study is discussed in subsequent sections.

## SECTION 7

## PURE CULTURE SETTLING VELOCITIES

Research on algal settling rates to date has attempted to describe settling velocity at a given temperature as a species-specific constant or as a range of values for a given species, depending upon physiological conditions of the algal cells such as cell nutrient status. This research effort was undertaken to determine the factors that control the settling rates of various algal species common to lagoons. The factors considered included temperature, light availability, algal species, and the presence or absence of dissolved oxygen.

Specifically, this research was to evaluate whether the temperature dependency of algal settling rates could be predicted by discrete settling theory as incorporated in Stokes Law:

$$v = \frac{g(\rho_s - \rho_l)d^2}{18\mu} \qquad (9)$$

where: $g$ = the acceleration of gravity ($m/s^2$),
$\mu$ = the absolute viscosity of the liquid, ($p_a$ - s),
$\rho_s$ = particle density ($kg/m^3$),
$\rho_l$ = liquid density ($kg/m^3$), and
$d$ = particle diameter (m ).

Also, this research was to evaluate whether the dark, anoxic environment within the rock filter would cause an alteration of algal settling velocity.

### EXPERIMENTAL METHODS

Three species of algae which are common to lagoons were selected for unialgal culture settling tests. Two of these pure cultures, Scenesdesmus acuminatus Lager and Chlorella vulgaris Beij, both green algae, were obtained from the Starr culture collection (University of Texas, Austin, Texas). The third culture, Microcystis aeruginosa Kutz. emend Elenkin, a blue-green alga, was obtained from the Environmental Protection Agency, National Environmental Research Center, Corvallis, Oregon. The cultures were maintained in a synthetic algal nutrient medium (18) and transferred weekly to insure a continuous supply of viable cells. A 14-hr light and 10-hr dark cycle was maintained using "cool-white" fluorescent bulbs at approximately 4000 lux. To insure the availability of $CO_2$, the pH was maintained below 8.5 by constant agitation with a wrist shaker with optimum surface to volume ratios (50 mℓ of sample in a 250 mℓ flask).

The fluorometric method used by Eppley, Holmes and Strickland (9) and modified for freshwater species by Titman (16) was used to determine the settling rates of the algae. This method measures the fluorescence of algal cells as they settle past an optical window under quiescent conditions. This technique allows rapid determination of sinking rate, usually requiring less than two hours.

The Turner Model III fluorometer was modified to measure the fluorescence of chlorophyll a, b and c (23) and a circulating water bath door was installed. A 10 mm inside diameter by 100 mm long cuvette was used as the sample chamber. The bottom 25 mm and the top 65 mm of the cuvette were covered with black tape. A sample aliquot of completely-mixed diluted algal culture was placed in the sample chamber so that the bottom of the meniscus was level with the upper edge of the clear 10 mm region. The cuvette containing the sample was placed in the fluorometer door, allowed to reach thermal equilibrium, removed and inverted several times to remix the sample, and then replaced in the door. Fluorescence was recorded until at least half the initial reading was reached. A schematic diagram of this fluorometric apparatus is given in Figure 7.

Several assumptions are involved in the use of this technique to measure average settling velocities. First, the physiological condition of the cells is assumed to not be adversely affected during the measurements. The time period involved in the test (usually less than two hours) helps minimize any physiological changes. Second, fluorescence readings are assumed to be directly proportional to cell concentration. For dilute samples (less than one mg/l), this appears to be valid (19). Third, settling in the sample chamber is assumed to be free from the effects of convection currents. Maintenance of a constant temperature in the sample chamber by use of a circulating water bath minimizes this effect. Finally, reductions in fluorescence are assumed to result from sinking of cells past the optical window and not from rising of cells toward the meniscus. This may not always be true, but it is easily checked.

A typical settling fluorometric settling curve is shown in Figure 8. The curve is typically linear to below 50 percent fluorescence and this portion of the curve defines the mean settling velocity $\bar{v}$ as the average distance cells sink divided by the time to reach 50 percent fluorescence. Since the algal cells are uniformly suspended initially, the average settling distance for a 50 percent reduction in fluorescence is one-half the height of the clear portion of the sample chamber, or five millimeters for our apparatus (20).

The non-linear region of the settling curve can be utilized to define the distribution of settling velocities within the sample tested (16). A small departure from linearity in this range indicates a narrow distribution of settling velocities, while a large departure indicates a broad distribution of settling velocities. Reasonable definition of the settling velocity distribution, however, requires that the settling test be continued to near 0 percent fluorescence. For slow settling samples, this may involve too long a time period for reasonable accuracy. Consequently, only mean settling velocities were determined for the pure culture settling tests conducted within this study.

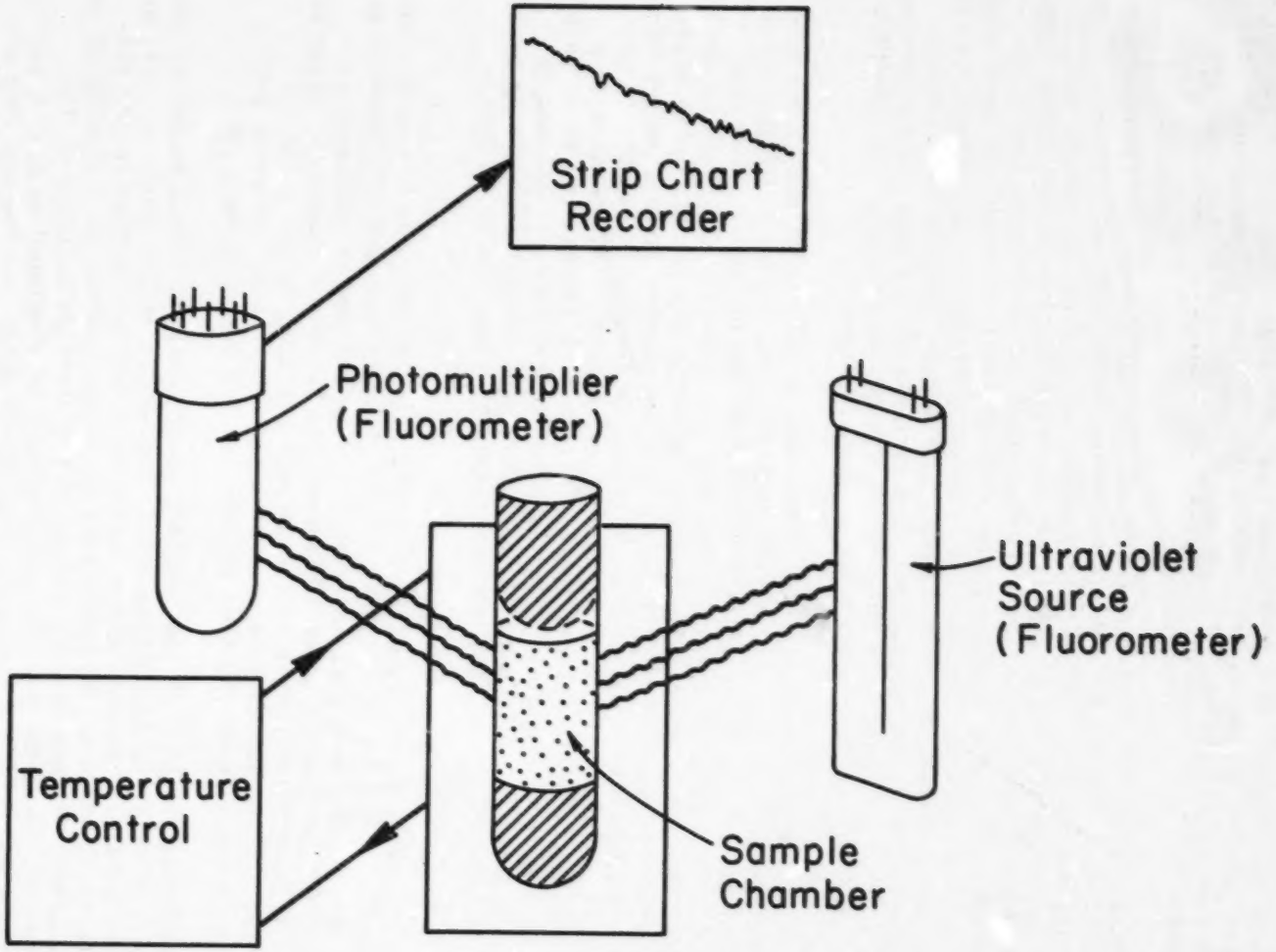


Figure 7. Schematic diagram of fluorometric apparatus for measuring algal settling rates.

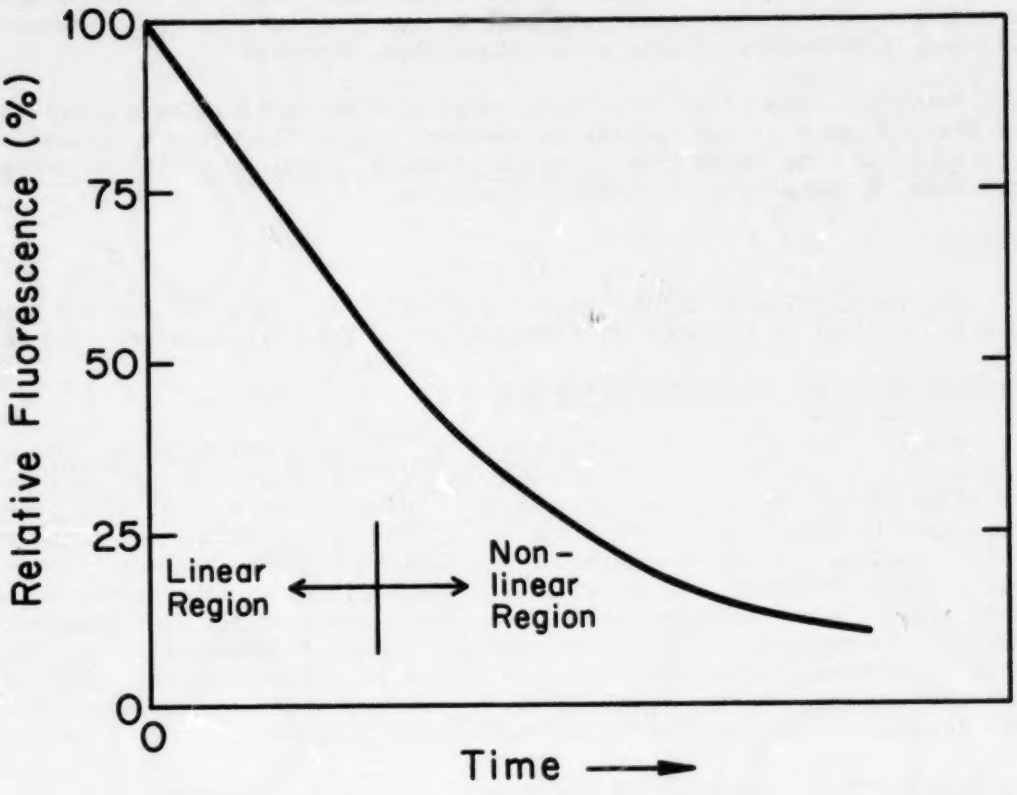


Figure 8. Typical fluorometric settling curve.

Settling rates were measured under varying environmental conditions typical of rock filters. First, settling rates were determined for cultures grown and maintained at four different temperatures: 5°C, 10°C, 15°C and 21°C. Settling rates were measured with the cuvette cooled to the same temperature as growth. Second, measurements were conducted for cultures that were placed in the dark at 21°C for a period of two weeks under either aerobic or anoxic conditions. The anoxic conditions were produced by purging the cultures with nitrogen in Erlenmeyer flasks with ground-glass stoppers.

Settling rates of mixed cultures were also measured in an attempt to assess the influence of one species on another. Equal fluorescent aliquots of S. acuminatus were mixed with C. vulgaris and S. acuminatus with M. aeruginosa at volume ratios of 2:1, 1:1, and 1:2 at 21°C.

## RESULTS

All three cultures tested appeared to exhibit a specific gravity greater than 1.0 in that no buoyant cells were observed following the settling tests.

### Settling Rates at Constant Temperature

The settling rates of S. acuminatus, C. vulgaris and M. aeruginosa at 21°C were 0.26 ± 0.13, 0.14 ± 0.05 and 0.13 ± 0.11 m/day, respectively (settling rate ± one standard deviation). The difference in settling rates for these species were found to be large enough that the performance of the rock filter could be altered depending on the dominant species present. These values were similar to the lowest values reported for various marine and freshwater algae. Large settling rates (> 1 m/day) observed for some seawater species were not observed for these species common to wastewater lagoons. Because these measurements were near the reasonable detection limit for the fluorometric techniques (approximately 0.1 m/day) (15), the standard deviations were large in comparison to the measured settling rates.

### Settling Rates at Variable Temperatures

The effects of temperature on settling rates of two pure cultures are shown in Figure 9. S. acuminatus sank about 3 times slower and M. aeruginosa, about 8 times slower at 5°C as compared to 21°C. Part, but not all, of the decrease in settling rates is attributable to the effect of decreasing viscosity as expressed by Stokes Law (see Eq. (9)). Over the typical temperature ranges of lagoons (5° to 20°C), settling rates would be affected by a factor of about 2.5 to 7.5. This is much larger than the differences measured for the three different species at 21°C.

The large influence of temperature above the predicted contribution of viscosity changes strongly suggests that the physiological condition of the algal cells are altered at lower temperatures. This may be due to smaller cell sizes or changes in mechanisms used to retard settling.

### Settling Rates After Dark Incubation

Algae settle in rock filters under dark conditions that may alter their

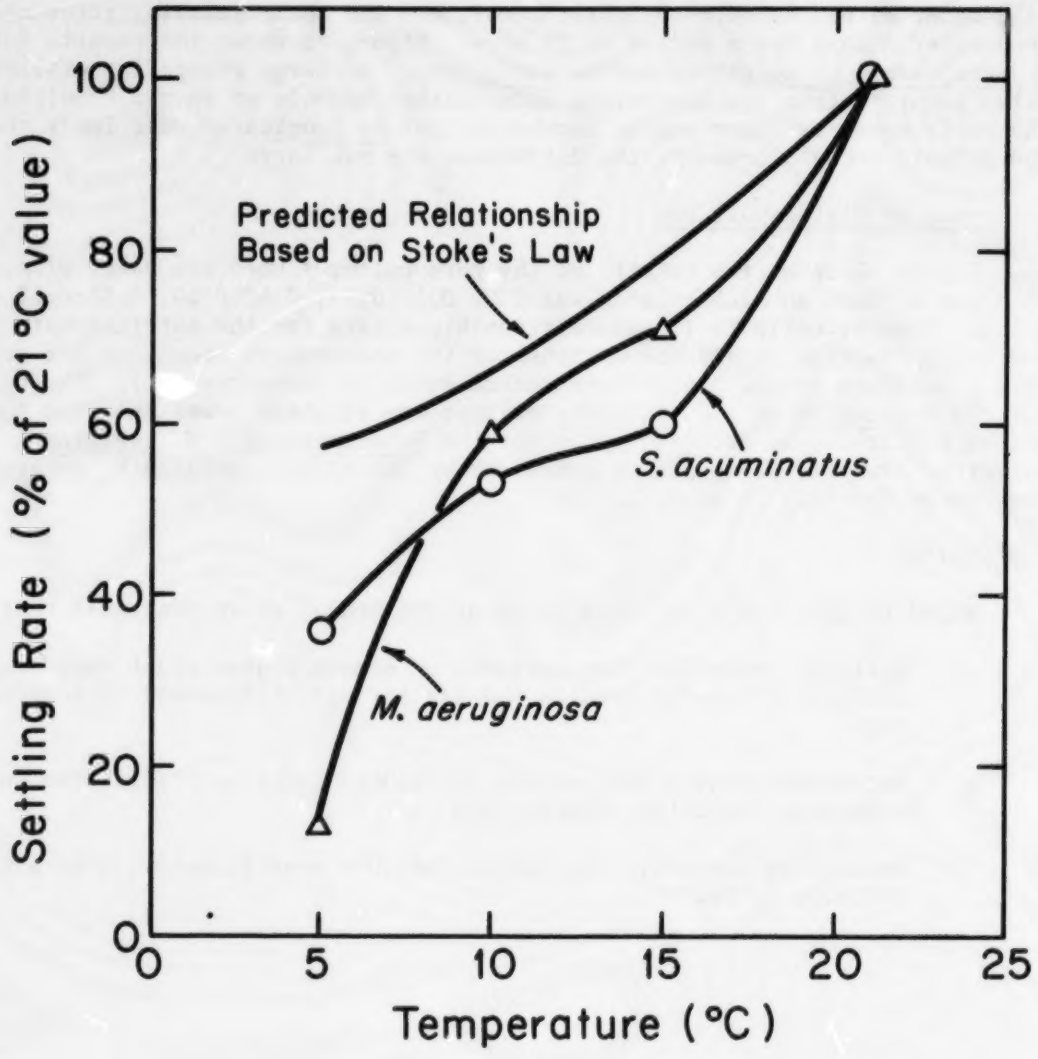


Figure 9. Algal settling rates vs. temperature for two cultures.

physiological condition and, subsequently, their settling rate. The conditions in rock filters may be either aerobic or anoxic. To determine the influence of these conditions, the three pure cultures were incubated in the dark at 21°C under either aerobic or anoxic conditions and their settling rates measured every 3 days for a period of 15 days. Figure 10 shows the results for S. acuminatus, C. vulgaris, and M. aeruginosa. No large change in settling rates occurred from the incubation under either aerobic or anoxic conditions. The settling rates under anoxic incubation for S. acuminatus were lower than the aerobic values; however, the difference was not large.

## Influence of Mixing Cultures

Figure 11 shows the results of the pure cultures when the ratio of algae a to algae b based on fluorescence was 1:0, 0.67:0.33, 0.50:0.50, 0.33:0.67 and 0:1.0. Theoretically, a linear relationship exists for the settling rate versus algal fraction if all assumptions for the measurement technique are valid (i.e., discrete settling and fluorescence equal to concentration). The results for the S. acuminatus - C. vulgaris mixture are slightly lower than the theoretical results. The settling rates for the S. acuminatus - M. aeruginosa mixtures, however, seemed to be dominated by the slower settling M. aeruginosa. The reason for this is unknown.

# CONCLUSIONS

Based on the results of this phase of the study, it is concluded that:

1) Settling rates for pure cultures of common lagoon algae vary significantly between species and are strongly influenced by temperature,

2) Decreased temperatures result in reduced algal settling rates in excess of viscosity effects, and

3) Aerobic or anaerobic incubation does not significantly alter algal settling rates.

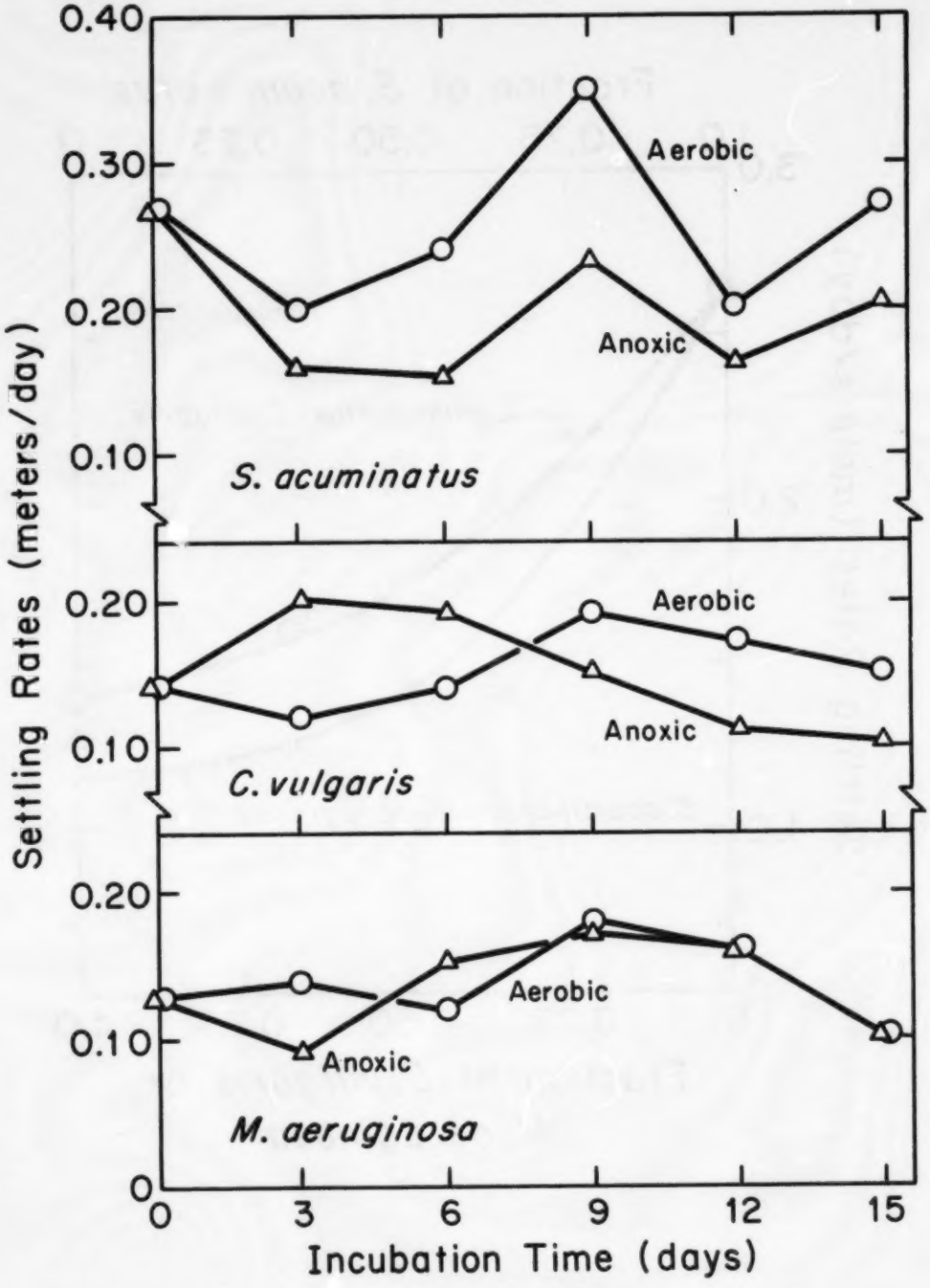


Figure 10. Settling rates for three cultures under aerobic and anoxic dark incubation at 21°C.

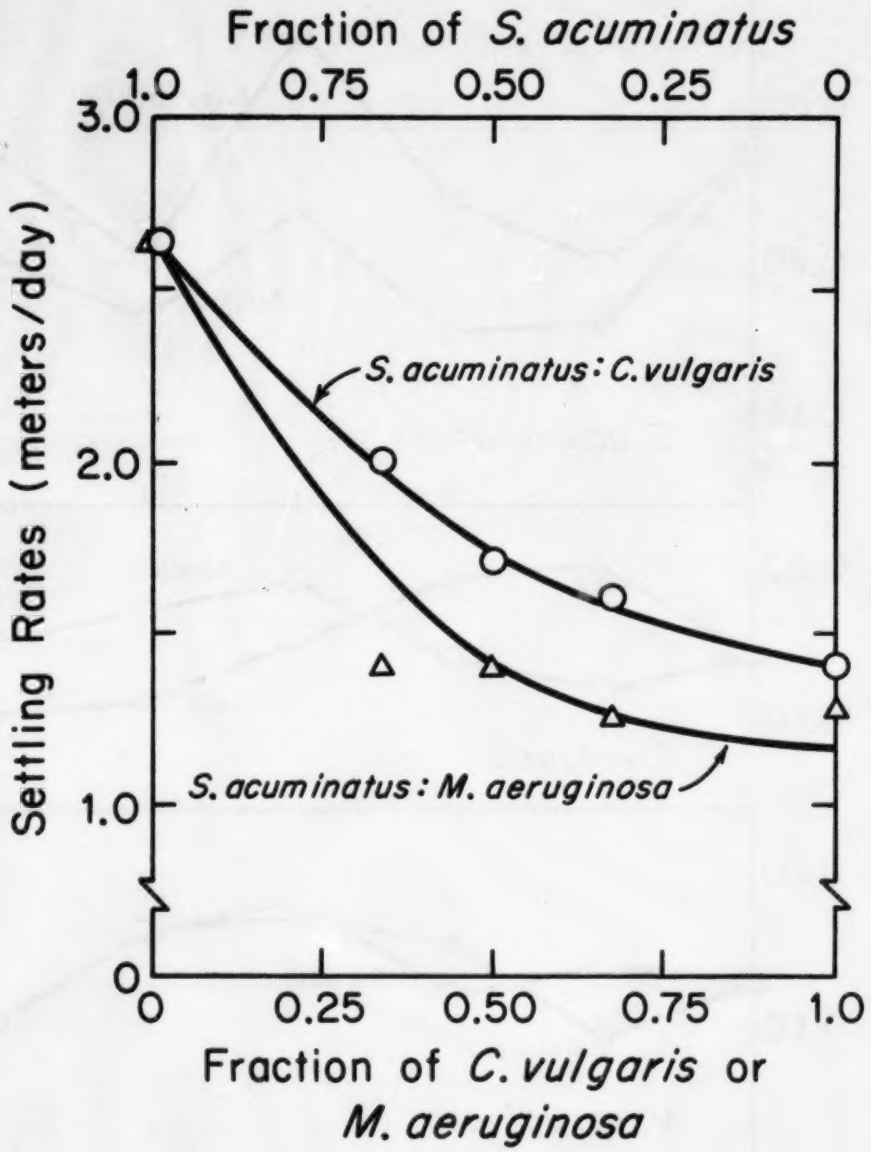


Figure 11. Settling rates for mixtures of pure cultures.

## SECTION 8

## EVALUATION OF VENETA ROCK FILTER

### SAMPLING AND ANALYTICAL METHODS

Samples were collected and analyzed for seven consecutive days out of each month over a one-year period. This schedule was chosen to provide data on both long-term and day-to-day performance without overextending available resources. Samples were collected from the rock filter influent (lagoon effluent) and the rock filter effluent as shown in Figure 1. Rock filter effluents were collected prior to chlorination so that interferences from chlorine would be eliminated in subsequent analysis.

A portable automatic sampler (ISCO model 1580) was installed at each sample point to collect 24-hour composite samples. The sample bottle in each sampler was packed in ice to bring sample temperature to 4°C or below. Composite samples were transferred to 1-liter plastic bottles and transported to the Corvallis laboratory for analysis of major wastewater constituents. Additionally, grab samples were collected for analysis of constituents whose concentration could be affected by automatic sampling or by storage for 24 hours. Grab samples were generally taken in the mid-afternoon. Temperature, dissolved oxygen, pH and sulfide analyses were performed on-site using grab samples.

Analysis of other constituents, including ammonia, nitrate, suspended solids (total and volatile), organic nitrogen, phosphorus, chlorophyll, $BOD_5$, COD, and TOC were performed on 24-hour composite samples. Composite samples were preserved by refrigeration at 0°C and the addition of 0.8 ml $H_2SO_4$ per liter.

An algal speciation and count was performed on one lagoon effluent and one rock filter effluent grab sample during each sampling period except the first two.

Additionally, algal settling rates were measured on lagoon effluent grab samples during several of the sampling periods. The settling tests were performed on undiluted samples by the fluorometric technique described previously. It should be noted that algal concentration may not be directly proportional to fluorescence at the high concentrations present in lagoon samples, but the use of undiluted samples was judged as most closely modeling conditions in the rock filter. The fluorometer was zeroed on sample filtrate so that the measured fluorescence was attributable only to algal cells. Samples in the settling chamber were maintained at the temperature of the lagoon effluent.

A summary of parameters analyzed, sample storage and analysis methods,

and equipment used is given in Table 5.

## RESULTS

### Operational History

The City of Veneta is required to meet secondary treatment standards from Nov. 1 to May 31 and is not allowed to discharge during the summer dry weather period (June 1 through October 31). Each spring the lagoon is drawn down to 0.76 m (2.5 ft) to allow for storage of all flows during the dry weather period. The rock filter is drained after discontinuance of discharge and left dry until the fall.

Discharge during the Fall 1977 was begun on November 11. The rock filter was filled with lagoon effluent and drained twice prior to startup. The sampling schedule used is shown in relation to weekly average flow rates in Figure 12. On approximately December 1, the discharge rate was set at the maximum pumping capacity (~ 2180 $m^3$/day) due to the extremely high lagoon levels (> 2 m) and maintained at that rate through March, 1978.

Beginning in the February sampling period, a sulfide odor was apparent in the vicinity of the rock filter effluent manhole. However, sulfides could not be measured above the minimum detectable concentration of the sulfide probe (0.1 mg/l). The sulfide odor was reduced, but still noticeable in March, April and May.

By mid-March, the high effluent pumping rate finally began to reduce the lagoon level. By April 10, the lagoon was drawn down to the minimum water level of 0.76 m (2.5 ft) and the discharge rate was reduced.

In the May sampling period, the lagoon level was at 0.9 m (3.0 ft) and an algal bloom was in progress. Lagoon effluent suspended solids were 33 mg/l at the beginning of the week and rose to 61 mg/l by the end of the week. At the end of the May sampling period, the rock filter was drained and left dry until the following sampling period.

A variance of the City's discharge permit was requested of the Oregon Department of Environmental Quality (DEQ) to allow discharge during the summer dry weather period. This request was made so that data on summer operation of the rock filter could be obtained. This request was granted by the DEQ based on the more stringent effluent limitations in Table 6.

TABLE 5. SUMMARY OF ANALYTICAL TECHNIQUES

| Parameter | Type of Sample | Sample Storage and/or Preservation | Method of Analysis | Reference |
|---|---|---|---|---|
| Temperature | Grab | On-site | Thermistor | |
| DO | Grab | On-site | Membrane electrode | (21),p. 450 |
| pH | Grab | On-site | Electronic pH meter | (21),p. 460 |
| $H_2S$ | Grab | On-site | Ion-specific electrode | (22) |
| $NH_4^+$ | 24-hour composite | On-site | Ion-specific electrode Known addition method | (21),p. 381 |
| $NO_3^-$ > 1 mg/l | 24-hour composite | On-site | Ion-speicific electrode Known addition method | (23) (27) |
| < 1 mg/l | 24-hour composite | Refrigeration @ 0°C + 0.8 ml $H_2SO_4$/1 | Brucine method | |
| TSS and TVSS | 24-hour composite | On-site filtration | Gravimetric | (21),p. 94, 96 |
| Organic N | 24-hour composite | Refrigeration at 0°C | Kjeldahl digestion Acidimetric finish | (21),p. 437 |
| Phosphorus (total and soluble) | 24-hour composite | On-site filtration. Refrigeration @ 0°C + 0.8 ml $H_2SO_4$/1 | Digestion with $H_2SO_4$ & $HNO_3$. Vanadomolybdophosphoric acid method. | (21),p. 466 |
| Chlorophyll | 24-hour composite | Immediate filtration | Spectrophotometric | (21),p. 1029 |
| $BOD_5$ | 24-hour composite | Immediate preparation | BOD bottle | (21),p. 543 |
| COD | 24-hour composite | Refrigeration at 0°C + 0.8 ml $H_2SO_4$/1 | Dichromate digestion | (21),p. 550 |
| TOC | 24-hour composite | Refrigeration at 0°C + 0.8 ml $H_2SO_4$/1 | TOC analyzer | (25),p. 532 |

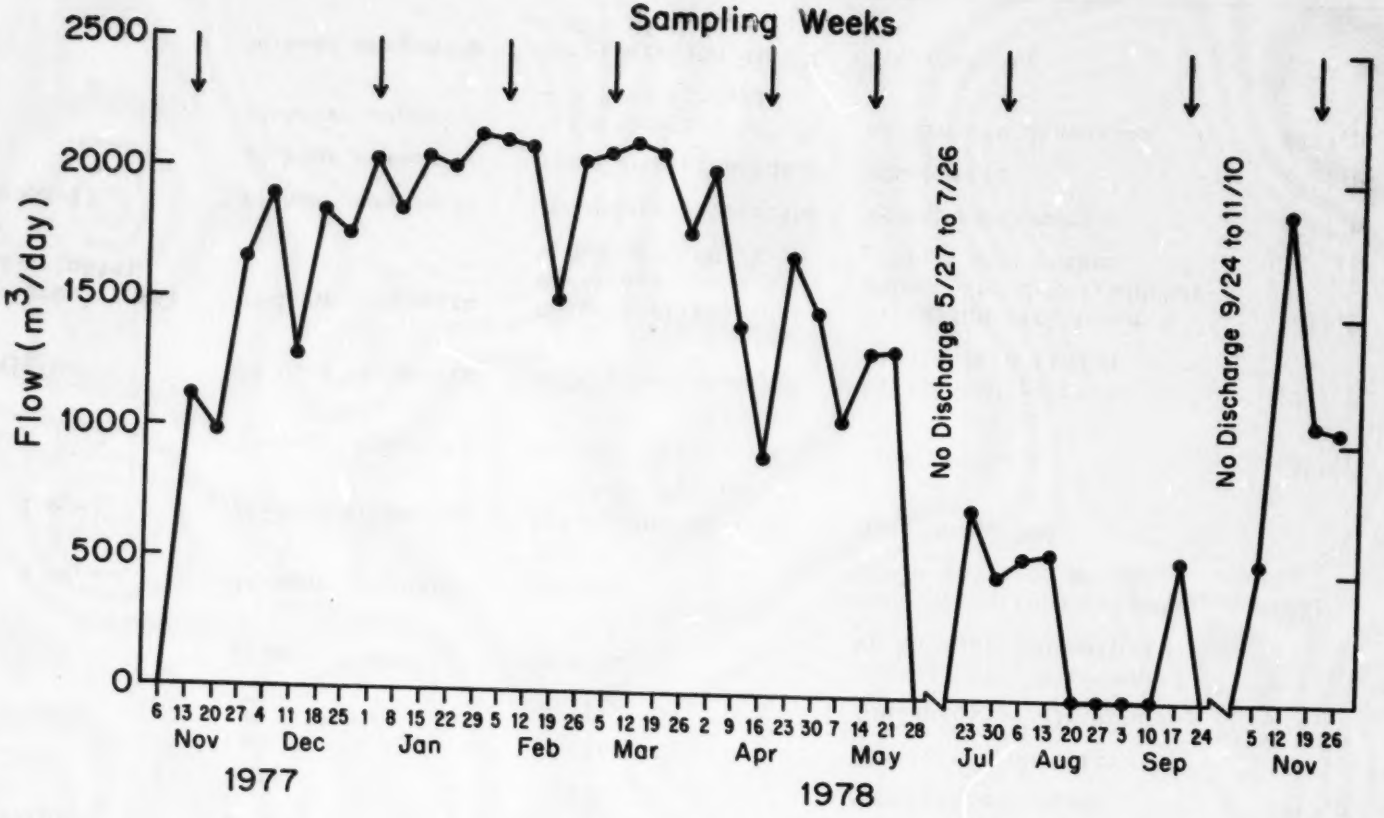


Figure 12. Weekly average effluent flow and sampling periods for Veneta rock filter.

TABLE 6. EFFLUENT LIMITATIONS DURING SUMMER, 1978

| Parameter | Monthly Average | Weekly Average | Daily Average |
|---|---|---|---|
| BOD | 10 mg/l | 15 mg/l | 20 mg/l |
| TSS | 10 mg/l | 15 mg/l | 20 mg/l |
| Fecal Coliform | 200/100 ml | 400/100 ml | - |
| pH | 6-9 | 6-9 | 6-9 |
| BOD/DF* | 1 | 1 | 1 |

*BOD in mg/l, DF = dilution factor in receiving stream

Due to the low lagoon level and the high evaporative rate during the summer, however, discharge was not begun until July 21 when the lagoon level reached 1.2 m (4.0 ft). By this time, a bloom of blue-green algae had caused the lagoon effluent TSS to exceed 100 mg/l.

The blue-green algal species that bloomed in July formed a thick (up to 10 cm), odorous mat in the first lagoon cell in August and caused the lagoon operators severe problems. The operators attempted to skim off the mat manually and to disperse it using an outboard motorboat with little success. Additionally, the low lagoon level required that discharge be discontinued in late August. Except for a one-week discharge period in September (for sampling purposes), no flow was discharged until November 10. The blue-green algal mat was still a problem during the September sampling period and lagoon effluent suspended solids were near 100 mg/l. Application of lime to the algal mat and colder temperatures in October eventually broke up the mat. By the November sampling period, the blue-green algae were absent from the lagoon and wet weather necessitated a higher discharge flow rate. A sulfide odor was again present at the rock filter effluent manhole during November.

## Analytical Results

A summary of rock filter influent and effluent data is shown in Table 7. These data are averages of the seven consecutive days of sampling during each sampling period. Daily data are tabulated in Appendix A. The hydraulic loading indicated is the pumped flow rate divided by the total rock filter volume ($m^3$ water/$m^3$ rock filter-day). The pH of the lagoon effluent approached 10 during summer periods of heavy photosynthesis, but the rock filter provided sufficient detention time without photosynthetic activity so that dissolved carbon dioxide was replenished and the pH lowered to between 7 and 8.

As mentioned previously, dissolved oxygen (DO) readings were taken on grab samples, generally in the mid-afternoon. Therefore, the influent (lagoon effluent) DO values do not represent the large diurnal variations in DO which

TABLE 7. DATA SUMMARY FOR VENETA ROCK FILTER

| Parameter | Weekly Averages for Week of 11/13/77 I* | 11/13/77 E* | 1/01/78 I | 1/01/78 E | 2/05/78 I | 2/05/78 E | 3/05/78 I | 3/05/78 E | 4/16/78 I | 4/16/78 E |
|---|---|---|---|---|---|---|---|---|---|---|
| Hydraulic Loading ($m^3/m^3$-day) | 0.13 | | 0.28 | | 0.28 | | 0.27 | | 0.07 | |
| Temperature (°C) | 8.4 | 8.6 | 6.0 | 6.3 | 9.3 | 9.0 | 10.6 | 9.8 | 12.3 | 11.5 |
| pH | 9.0 | 7.7 | 8.6 | 7.1 | 7.6 | 7.1 | 7.9 | 7.1 | 8.7 | 7.2 |
| DO (mg/l) | 10.1 | 4.5 | 15.4 | 6.2 | 11.2 | 3.2 | 10.8 | 3.0 | 10.8 | 3.2 |
| TSS (mg/l) | 42 | 9 | 29 | 14 | 28 | 10 | 22 | 9 | 44 | 7 |
| TVSS (% of TSS) | 83 | 89 | 90 | 89 | 90 | 86 | 89 | 86 | 92 | 66 |
| $BOD_5$ (mg/l) | 20 | 9 | 27 | 14 | 20 | 10 | 21 | 15 | 39 | 19 |
| Soluble COD (mg/l) | - | - | - | - | - | - | - | - | - | - |
| Total COD (mg/l) | 121 | 77 | 67 | 45 | 51 | 36 | 61 | 44 | 147 | 80 |
| TOC (mg/l) | 37 | 28 | 24 | 16 | 19 | 13 | 23 | 16 | - | - |
| $NH_4^+$-N (mg/l) | 0.8 | 1.7 | 3.5 | 2.9 | 15.5 | 12.4 | 15.9 | 14.3 | 3.8 | 5.5 |
| Org-N (mg/l) | 4.1 | 3.4 | 5.8 | 5.4 | 5.7 | 1.4 | 3.9 | 3.3 | 8.8 | 4.5 |
| $NO_3^-$-N (mg/l) | 1.5 | 2.1 | 1.0 | 1.6 | 0.8 | 1.1 | 1.1 | 0.8 | 1.7 | 1.5 |
| Soluble P (mg/l) | 4.8 | 3.9 | 1.7 | 1.6 | 2.5 | 2.6 | 2.1 | 3.5 | 6.0 | 4.6 |
| Total P (mg/l) | 5.2 | 4.1 | 2.1 | 1.6 | 3.2 | 3.4 | 2.7 | 3.1 | 6.8 | 5.0 |
| Chlorophyll a (µg/l) | - | - | 340 | 160 | 260 | 72 | 160 | 32 | 690 | 13 |
| Chlorophyll b (µg/l) | - | - | 39 | 23 | 59 | 15 | 17 | 3 | 348 | 12 |
| Chlorophyll c (µg/l) | - | - | 23 | 15 | 29 | 6 | 19 | 5 | 148 | 22 |
| Sulfides (mg/l) | ND | ND | ND | ND | ND | <0.1 | ND | <0.1 | ND | ND |

(continued)

TABLE 7. (Continued)

| Parameter | Weekly Averages for Week of 5/14/78 I | 5/14/78 E | 7/30/78 I | 7/30/78 E | 9/17/78 I | 9/17/78 E | 11/19/78 I | 11/19/78 E |
|---|---|---|---|---|---|---|---|---|
| Hydraulic Loading ($m^3/m^3$-day) | 0.17 | | 0.07 | | 0.06 | | 0.13 | |
| Temperature (°C) | 18.2 | 17.0 | 22.0 | 20.8 | 14.5 | 13.8 | 5.6 | 5.4 |
| pH | 9.9 | 7.3 | 9.6 | 7.6 | 9.2 | 7.5 | 7.6 | 7.2 |
| DO (mg/l) | 17.4 | 2.9 | 6.9 | 1.8 | 6.4 | 2.6 | 10.2 | 4.5 |
| TSS (mg/l) | 43 | 9 | 105 | 10 | 84 | 10 | 48 | 11 |
| TVSS (% of TSS) | 84 | 85 | 88 | 67 | 87 | 66 | 87 | 80 |
| $BOD_5$ (mg/l) | 42 | 18 | 43 | 11 | 56 | 15 | 42 | 19 |
| Soluble COD (mg/l) | - | - | 72 | 76 | 98 | 82 | 70 | 69 |
| Total COD (mg/l) | 159 | 104 | 183 | 90 | 201 | 85 | 189 | 91 |
| TOC (mg/l) | 56 | 39 | 69 | 38 | 64 | 32 | - | - |
| $NH_4^+$-N (mg/l) | 2.6 | 7.2 | 0.2 | 3.5 | 1.8 | 4.6 | 6.6 | 4.6 |
| Org-N (mg/l) | 8.4 | 5.2 | 15.3 | 6.5 | 15.8 | 5.9 | - | - |
| $NO_3^-$-N (mg/l) | 2.3 | 1.0 | 1.9 | 1.2 | 1.2 | 0.9 | 2.6 | 2.6 |
| Soluble P (mg/l) | 3.7 | 4.9 | - | - | - | - | - | - |
| Total P (mg/l) | 5.6 | 5.4 | - | - | - | - | - | - |
| Chlorophyll a (µg/l) | 210 | 34 | 234 | 15 | 427 | 39 | 179 | 44 |
| Chlorophyll b (µg/l) | 240 | 38 | 156 | 18 | 133 | 17 | 230 | 63 |
| Chlorophyll c (µg/l) | 380 | 80 | 165 | 39 | 34 | 12 | 474 | 168 |
| Sulfides (mg/l) | ND | ND | ND | ND | ND | ND | - | - |

* I = rock filter influent, E = rock filter effluent
ND = not detectable (<< 0.1 mg/l)

occur in lagoons. The rock filter dampens these diurnal variations to a large extent so that the effluent DO values shown are probably representative of average conditions. However, DO measurements taken below the effluent weirs during the summer months indicated that rock filter effluent DO values were consistently below 1.0 mg/l, while values at the sampling manhole were up to 3 mg/l higher. Apparently reaeration was resulting from drops over the weirs and into the effluent manhole.

Weekly average rock filter influent and effluent $BOD_5$ and TSS values over the study period are shown in Figure 13. Good suspended solids removals (> 70%) were obtained beginning with the first sampling on November 13, 1977, 2 days after the Fall startup.

Percentage removals of suspended solids were lower during the winter months of January, February, and March due to the high effluent pumping rate, but the lower algal concentrations in the lagoon effluent during these months resulted in final effluent $BOD_5$ and TSS values of less than 20 mg/l on all days sampled.

Weekly average effluent TSS did not exceed 15 mg/l during the study period and were generally not greater than 10 mg/l. Daily effluent TSS values exceeded 15 mg/l on only one occasion. Weekly average effluent $BOD_5$ values did not exceed 20 mg/l and daily values did not exceed 30 mg/l during the study period.

Ammonia-nitrogen was observed to increase noticeably in passing through the rock filter during the warmer months (Figure 14). This is apparently the result of increased biological degradation rates at these times. Due to the existence of both aerobic and anoxic zones in the rock filter at most times, both nitrification and denitrification are possible, even simultaneously. A small amount of nitrification appeared to occur during the colder months, changing to an apparent predominance of denitrification in the summer. The amount of biological nitrification and denitrification that can be supported in a rock filter, however, is definitely limited; nitrification by the limited oxygen content in the influent stream and denitrification by variations in the extent of the anoxic zone.

Chlorophyll concentrations are indicative of viable algae and removal can be directly correlated with suspended solids removal as shown in Figure 15. Variations in the proportion of chlorophylls a, b and c between sampling periods are indicative of changes in dominant algal species.

Beginning in March, 1978, grab samples were analyzed once each sampling period for algal species and counts. Results of this analysis are contained in Appendix B. These results indicate that green algae and flagellate algae were the most common classes present. The massive bloom of blue-green algae (Anacystis cyenea) that occurred during the summer of 1978 was unprecedented at the Veneta lagoon.

Results of the fluorometer settling rate analyses are shown in Table 8. The sample taken August 4 was completely dominated by the blue-green alga Anacystis cyanea. Observation of the settling chamber in the fluorometer

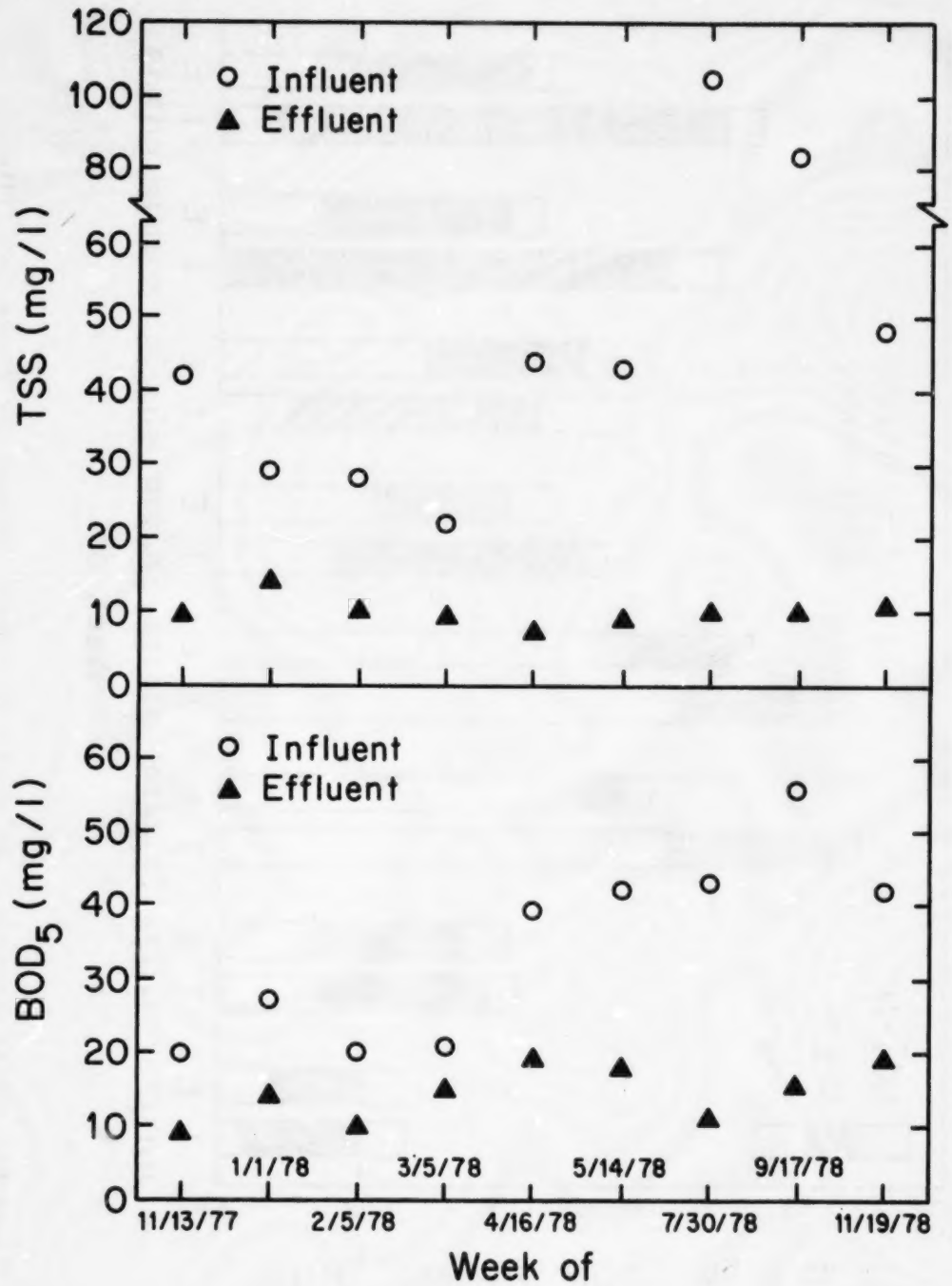


Figure 13. Weekly average TSS and $BOD_5$ for Veneta rock filter.

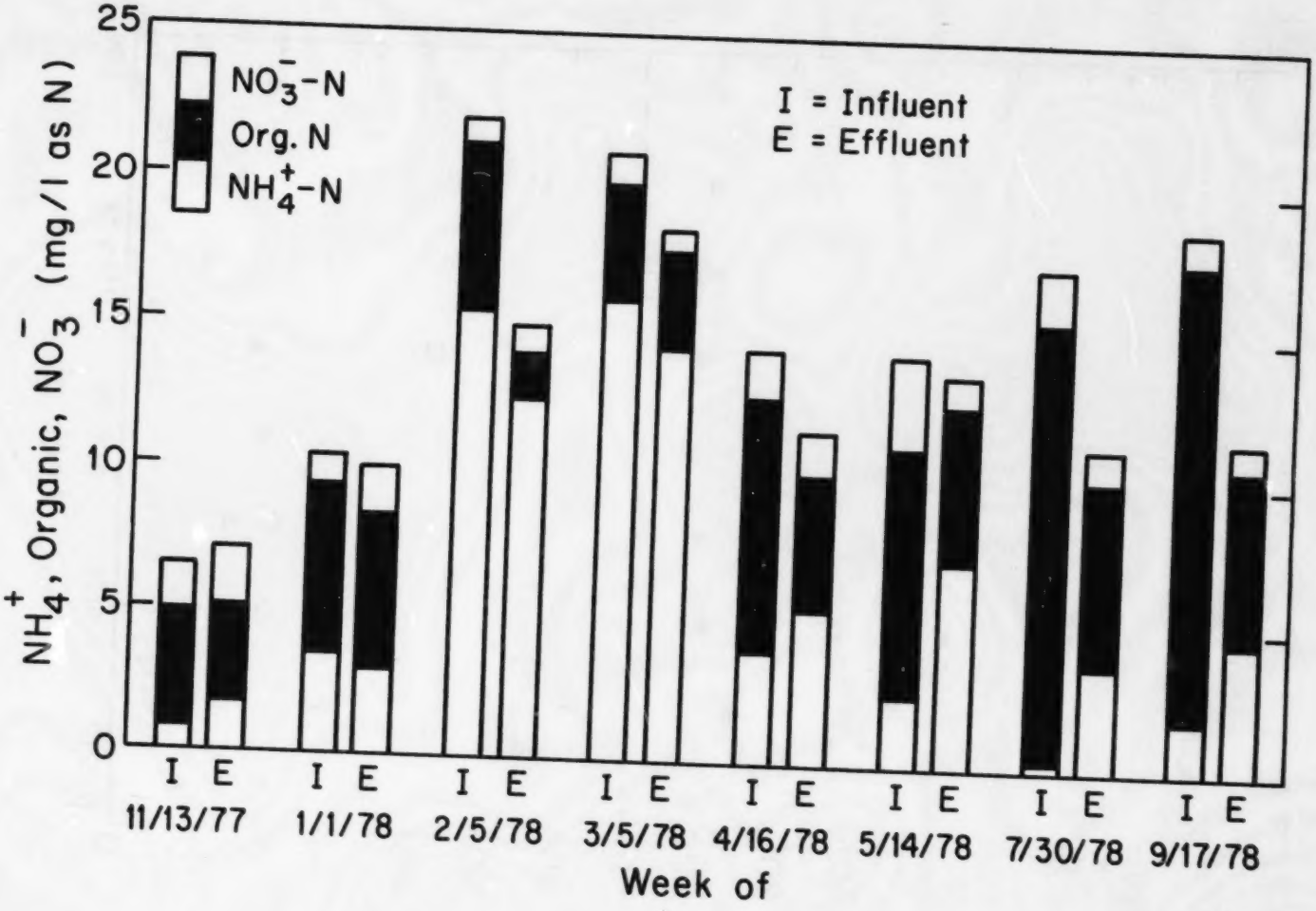


Figure 14. Weekly averages of influent and effluent nitrogen for Veneta rock filter.

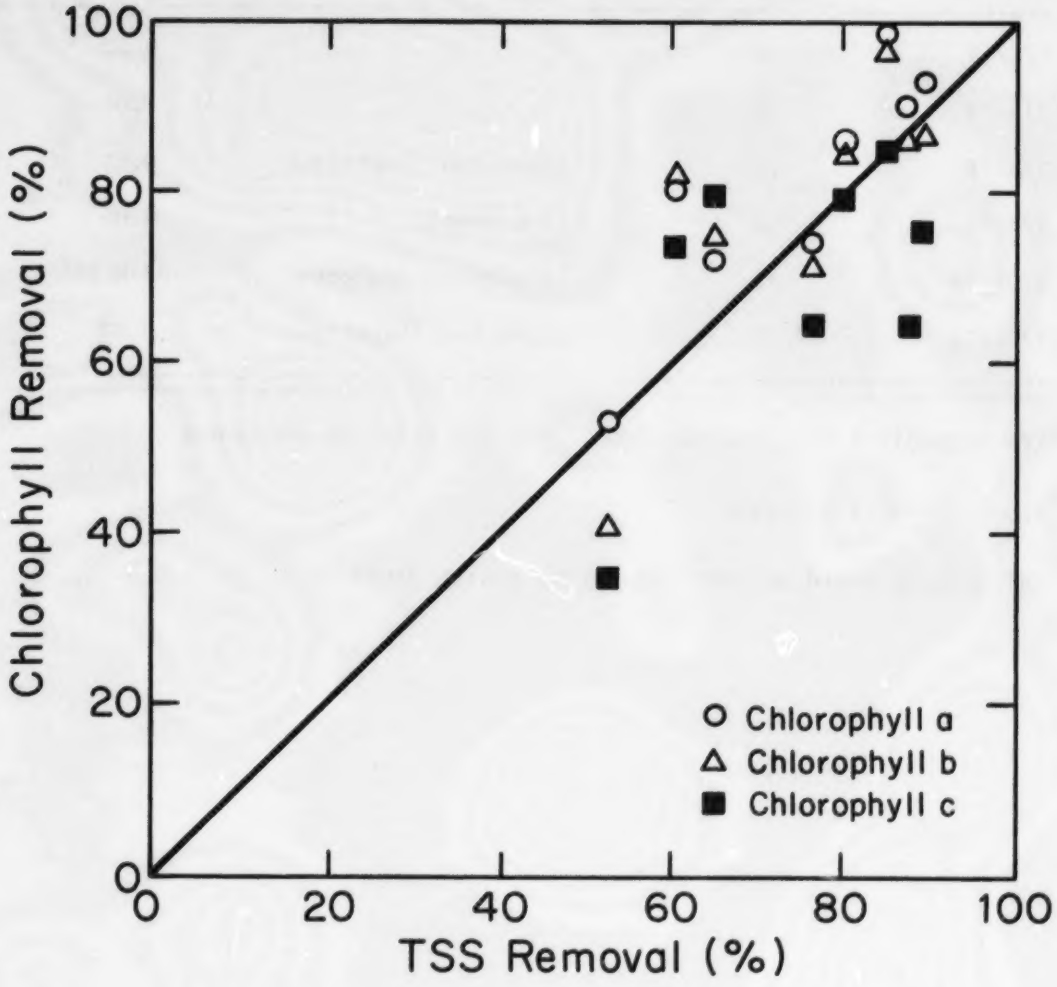


Figure 15. Correlation of chlorophyll to TSS removal for Veneta rock filter.

TABLE 8. MEAN SETTLING VELOCITIES FOR LAGOON SAMPLES

| Sample Date | Lagoon Temperature (°C) | Dominant* Class | Mean Settling Velocity (m/day) |
|---|---|---|---|
| 1/3/78 | 5 | - | 0.02 |
| 2/4/78 | 9 | - | 0.06 |
| 2/5/78 | 10 | green and flagellate | 0.08 |
| 8/4/78 | 22 | blue-green | 0.05[+] |
| 9/21/78 | 15 | blue-green and green | 0.03-0.21[†] |
| 11/25/78 | 5 | green and flagellate | 0.07 |

*See Appendix B for complete speciation and relative abundance

[+]Approximate rising rate

[†]Calculation based on settling versus rising distance

indicated that these algae were leaving the optical window by rising into the meniscus above and not by sinking. The mean velocity was therefore calculated as a rising velocity using the approximate rising distance in the settling chamber. It should be noted that our apparatus was not set up to measure rising rates, and this value is therefore approximate. Rising was still dominant during the September 21 analysis, but settling was also occurring. Because the rising and settling distances are different in the sample chamber, it was not possible to calculate a single velocity.

The mean settling velocities measured did not show a distinct correlation with temperature, but seemed to be clustered around about 0.05 m/day. Rising velocities for samples dominated by blue-green algae were similar to settling velocities of other samples.

It should be noted that the measured settling velocities in Table 8 are at or below the reported reasonable detection limit of the fluorometric technique (0.1 m/day). Values in this range have been reported in the literature (14), but the possible inaccuracy of such measurements are noted.

## Physical Observations

During May, 1978, the rock filter was excavated at one point to below the water line and the rocks were examined. The rocks were covered with a brown and green slime layer with a thickness of 1-3 mm. A distinct feature of the slime layer was that it was located primarily on the top surface of the rocks and the bottom surfaces were relatively clean, indicating that settling had been the algal removal mechanism. During September, 1978, (after the blue-green algal bloom) the rocks were again examined. It was then observed that the bottom surfaces of the rocks were also covered with a slime layer. Additionally, a brown scum layer of 1-2 cm thickness had formed at the water surface of the rock filter. These observations indicate that flotation was a primary mechanism operating in the removal of blue-green algae.

## Evaluation of Results

The mathematical model based on discrete settling theory presented in Section 6 suggested that for a given settling rate distribution, the removal efficiency of suspended solids should most directly be a function of hydraulic loading rate in the range of removals observed at the Veneta rock filter. A plot of weekly average TSS removal efficiency versus hydraulic loading rate for the nine sampling periods of this study is shown in Figure 16. The good correlation obtained for a linear relationship suggests that the algal settling (or rising) velocities did not vary greatly for the different sampling periods, despite the differences in dominant algal species, temperature, and other environmental conditions.

In accordance with settling theory, BOD removal in the rock filter should be through the removal of particulate BOD, primarily algae. This relationship is shown in Figure 17 as a correlation of $BOD_5$ and TSS removal. The straight line suggests a removal of about 0.5 mg $BOD_5$ per mg of suspended solids.

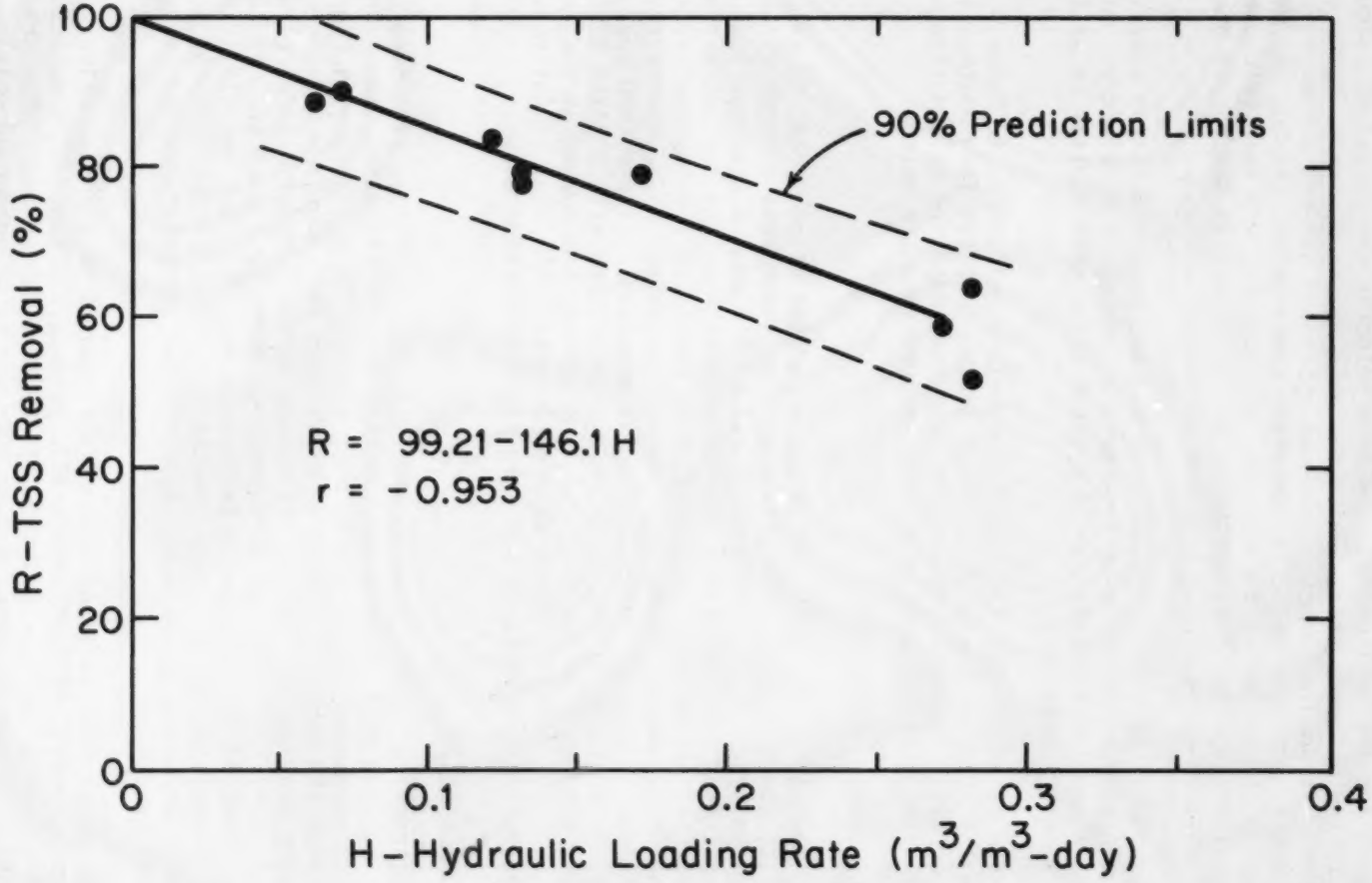


Figure 16. TSS removal vs. hydraulic loading rate for Veneta rock filter.

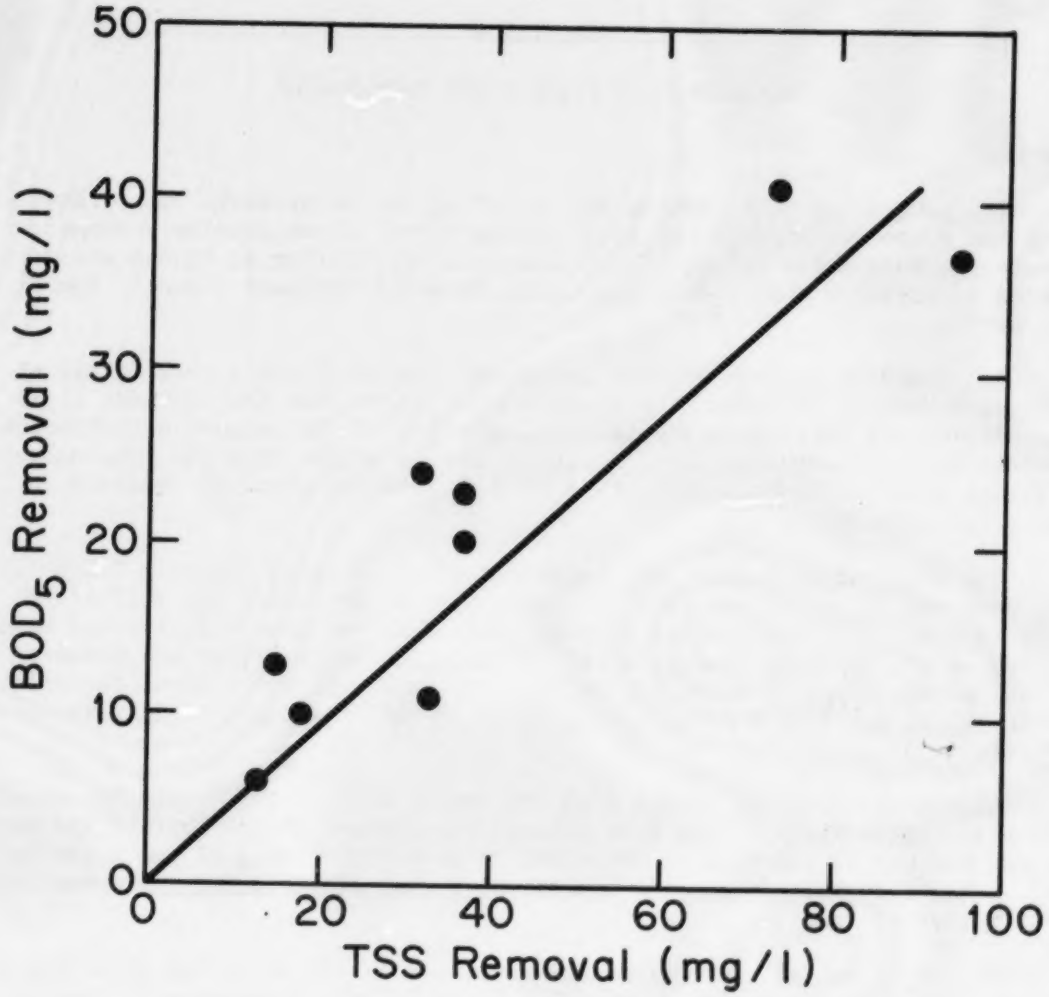


Figure 17. Correlation of $BOD_5$ to TSS removal for Veneta rock filter.

## SECTION 9

## EVALUATION OF PILOT-SCALE ROCK FILTER

### PURPOSE

The purpose of constructing and operating the pilot-scale rock filter was to allow a greater range in applied loading rates and to provide a comparison to the full-scale system. The full-scale rock filter at Veneta was suspected of having a poor flow distribution from the influent channel, limiting its performance.

Additionally, it was desired to operate the pilot-scale rock filter at varying hydraulic loadings over a short time period when the influent algal composition was relatively constant. Comparison of the removal efficiencies thereby obtained with the algal settling curve obtained from the fluorometric settling test would allow estimation of the effective settling distance in the pilot-scale filter.

The pilot-scale rock filter consisted of a Plexiglas channel, 7.6 m (25 ft) long and 38 cm (15 in) deep. Total volume of the model was 1.33 $m^3$ (46.7 $ft^3$) (Figure 18). Clean rocks were obtained from the Veneta filter and hand-placed in the channel. The porosity of the pilot-scale filter was measured as 40 percent compared to 42 percent for the Veneta filter. Thus, the pilot-scale filter was judged to be fairly close to the operational filter in media construction.

Lagoon effluent was pumped from the second cell of the Veneta lagoon to the pilot-scale filter. The flow entered the channel at the base of the media at one end and flowed through the media to an effluent weir at the opposite end. This flow pattern closely approximates that designed for the operational rock filter at Veneta.

The experimental rock filter was initially filled at a high rate from the Veneta lagoon system during July, 1978. Once filled, the hydraulic loading rate was reduced to a nominal value for about 8 days to allow stabilization of the unit. At this time, flow monitoring and sampling was begun. Hydraulic loading rates through the unit were varied from 0.119 to 0.532 $m^3/m^3$-day, representing anticipated values for rock filters.

Samples of both influent and effluent were taken after a steady-state situation was reached for each change in loading rate. The effluent samples were obtained from the wet well located below the effluent weir and the influent samples were obtained from the influent line (Figure 18). Analysis of each was made to determine $BOD_5$, TSS and TVSS in accordance with previously described methods.

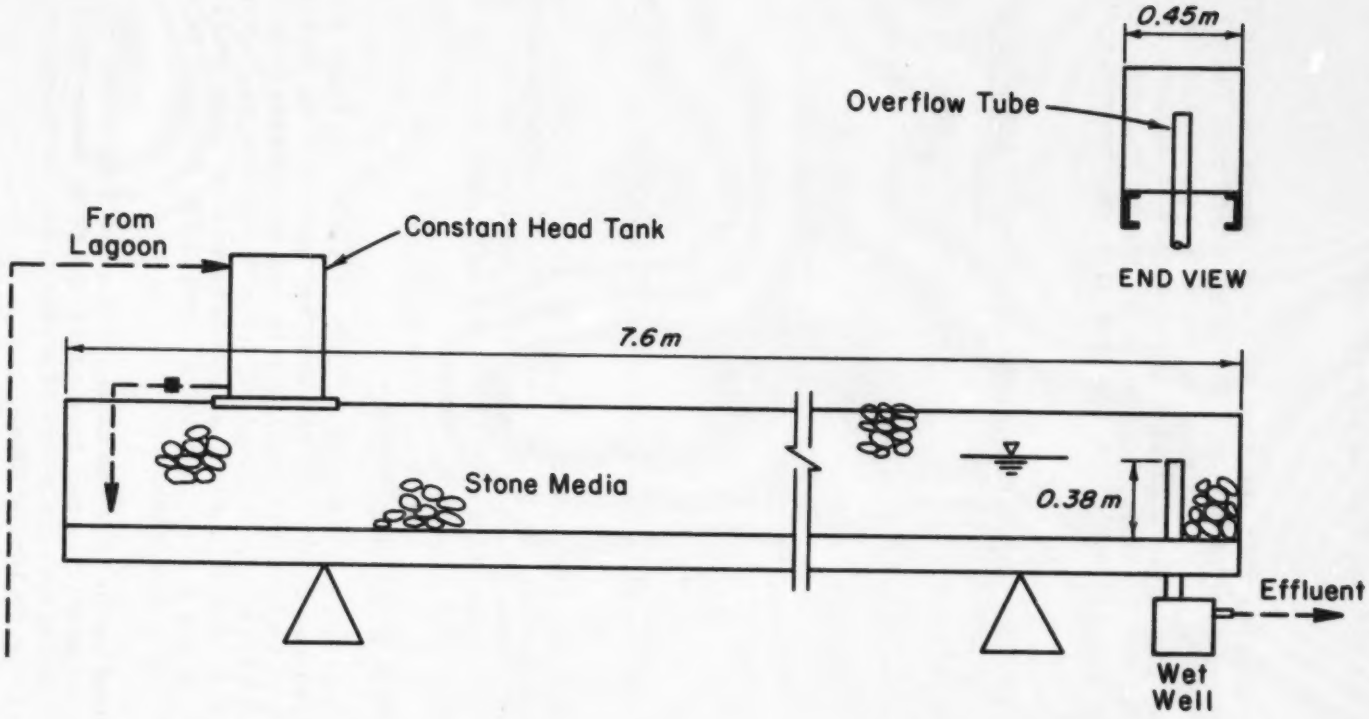


Figure 18. Pilot-scale rock filter.

An estimate of the resuspension rate of algae trapped within the interstices of the rocks and on the rocks was made by running tap water through the filter and measuring TSS and TVSS of the effluent.

## RESULTS

A tracer study indicated that the flow scheme in the pilot-scale filter resulted in a nearly plug-flow condition. The pilot-scale rock filter was operated during July and August, 1978 when lagoon suspended solids levels were exceeding 100 mg/l due to the bloom of blue-green algae. A summary of removal efficiencies at the various hydraulic loading rates (based on total volume) tested is shown in Table 9 and a plot of TSS removal versus hydraulic loading is shown in Figure 19.

TABLE 9. TSS, TVSS, AND $BOD_5$ REMOVAL OBTAINED BY THE PILOT-SCALE ROCK FILTER

| Hydraulic Loading Rate ($m^3/m^3$-day) | Percent Removal | | |
|---|---|---|---|
| | TSS | TVSS | $BOD_5$ |
| 0.119 | 87 | 88 | 84 |
| 0.250 | 86 | 87 | 74 |
| 0.391 | 74 | 75 | 50 |
| 0.532 | 70 | 71 | 47 |

Removal efficiencies for $BOD_5$ were similar to those for TSS at lower loading rates, but were smaller at the higher loading rates. This indicates the presence of a large fraction of soluble $BOD_5$ in the effluent at the higher loadings, but it is not known whether this was released from the filter or was initially present in the lagoon effluent.

### Estimating the Effective Settling Distance

The algal settling curve for August 4, 1978 is shown in Figure 20. This settling curve was obtained as part of the analyses conducted in evaluating the full-scale filter. Because the testing date was approximately in the middle of the pilot-scale filter operational period and the same blue-green alga was dominant during this entire period, it was assumed that this settling curve was applicable to the entire operational period for purposes of estimating the effective settling distance.

It should be noted again that the blue-green algae dominating the lagoon during this time period were observed to rise in the fluorometer settling chamber. Figure 20, therefore, describes the reduction in fluorescence due to the algae rising past the optical window.

If fluorescence is assumed to be proportional to algal concentration and

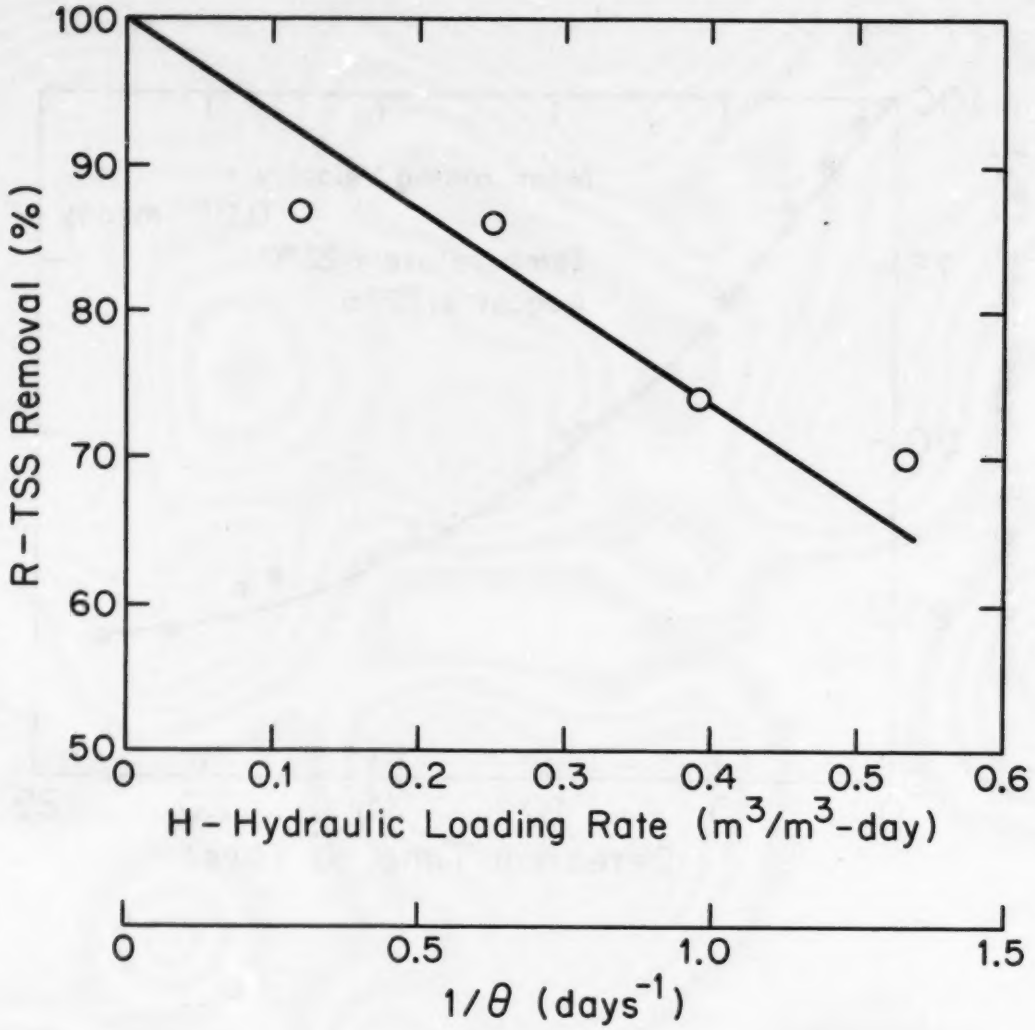


Figure 19. TSS removal vs. hydraulic loading for pilot-scale rock filter.

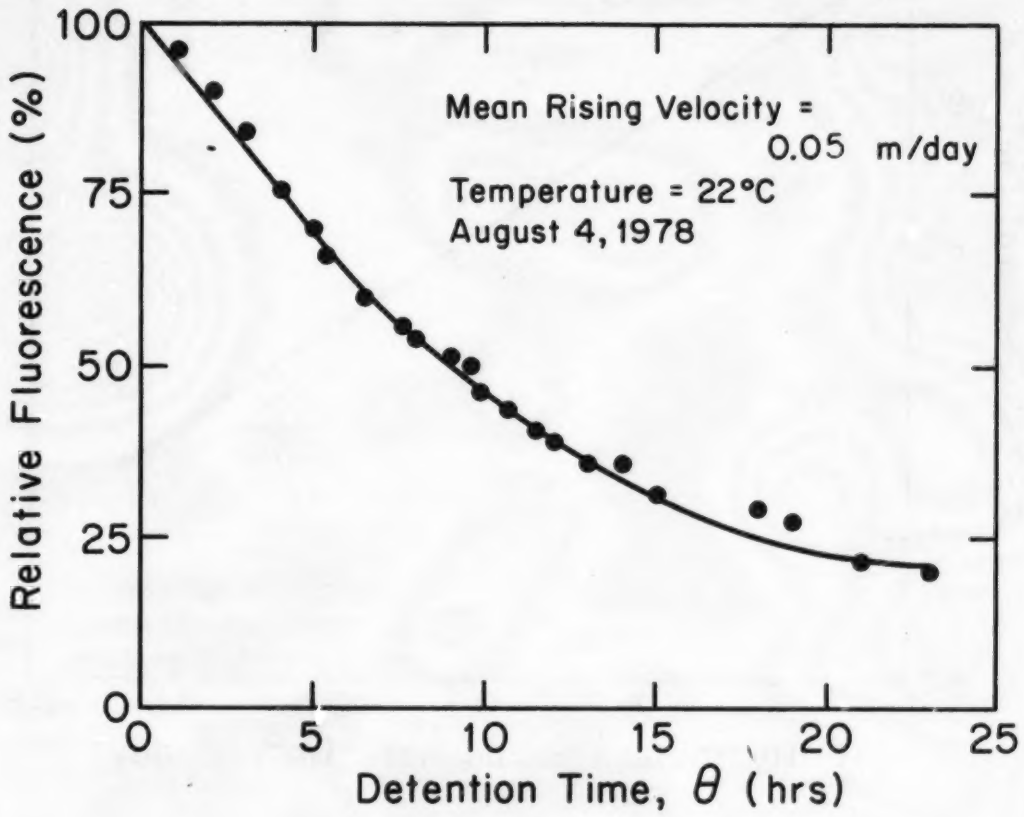


Figure 20. Algal settling curve for August 4, 1978.

therefore, to suspended solids concentration, then the algal removal curve shown in Figure 20 for the fluorometric settling test can be correlated with the removal efficiencies observed for the rock filter (Figure 19). Using these assumptions, the settling curve in Figure 20 was converted into a plot of suspended solids removed versus the inverse of the detention time. Figure 19 shows the same function for the pilot-scale filter operation ($1/\theta = H/p$).

According to the mathematical model of settling presented in Section 6, equivalent removals can be obtained for two different settling depths only when $\theta/d_s$ is the same. Using this requirement, the effective settling depth in this pilot-scale rock filter can be calculated as shown in Table 10. These calculations indicate an effective settling depth of about 4 cm in the rock filter.

An attempt to see if the resuspension of previously settled algae by hydraulic shear contributed significantly to the solids content of the effluent was initiated using clean water as the influent to the experimental filter. A hydraulic loading of 0.545 $m^3/m^3$-day was used, corresponding to the maximum loading previously applied. The average TSS of the effluent was found to be less than 3 mg/l; TVSS, less than 2 mg/l. It was concluded that resuspension of algae will not contribute significantly to effluent solids.

TABLE 10. CALCULATION OF EFFECTIVE SETTLING DEPTH IN PILOT-SCALE ROCK FILTER

| Pilot Filter Performance | | | 1/θ in fluorometer for same R ($days^{-1}$) | Effective Settling Depth $d_s$ (cm) |
|---|---|---|---|---|
| H ($m^3/m^3$-day) | 1/θ ($days^{-1}$) | R (%) | | |
| 0.119 | 0.298 | 87 | 0.600 | 7.0 |
| 0.250 | 0.625 | 86 | 0.647 | 3.6 |
| 0.391 | 0.978 | 74 | 1.20 | 4.3 |
| 0.532 | 1.33 | 70 | 1.39 | 3.7 |

# SECTION 10

# DISCUSSION

## REMOVAL MECHANISM

As discussed in Section 5, the classes of algae typically dominant in lagoons (green algae and flagellates) will settle under the dark, quiescent conditions present in rock filters. The pure culture settling tests, settling tests on lagoon samples and the performance analysis and physical observations of the Veneta rock filter all confirmed that sedimentation was the primary mechanism by which these algae were removed within the rock filter.

The massive bloom of blue-green algae that occurred during this study at the Veneta lagoon offered a unique opportunity to observe the behavior of this class of algae in settling tests and in a rock filter. The literature reviewed in Section 5 suggested that, under the dark, nutrient-rich conditions present in rock filters, gas vacuole formation would occur and these algae would rise in response to an absence of light. The lagoon effluent settling tests indicated that these algae were rising at measurable velocities and physical observations of the Veneta rock filter indicated that flotation was a major removal mechanism during the time period of blue-green algal dominance.

The apparent settling behavior of the blue-green alga Microcystis aeruginosa during the pure culture settling tests must be attributed to the culturing or settling rate measurement techniques and not regarded as typical behavior for blue-green algae in rock filters. A probable explanation for the apparent settling behavior is that the light from the fluorometer lamp affected the algae and, therefore, the behavior observed was not representative of dark conditions. The dilute algal concentrations utilized in the pure culture settling tests required a larger opening for the fluorometer lamp than the undiluted lagoon samples subsequently tested. This may explain the contrary observation of rising behavior during lagoon sample settling tests.

One topic not extensively discussed to this point is that of the rock-algae attachment mechanism. Once the algae have settled upon the rock surfaces, some form of attachment must occur in order for resuspension to be prevented at higher hydraulic loadings. Tests on the pilot-scale filter indicated that resuspension of settled algae was not significant. Natural biological attachment mechanisms may be functioning initially to prevent resuspension. Observation of rocks within the Veneta rock filter showed that, after sufficient time, a gelatinous slime layer of organic material formed on the rocks that could not be easily removed. These observations imply that cleaning of rocks within rock filter beds by flushing may not be practical.

## COMPARISON OF FULL-SCALE AND PILOT-SCALE FILTERS

The TSS removal efficiency as a function of hydraulic loading for the pilot-scale and the full-scale rock filter at Veneta are compared in Figure 21. This figure shows that the pilot-scale filter was capable of achieving similar removals to the full-scale filter at approximately twice the hydraulic loading. This difference is attributed to the poor flow distribution and hydraulic short-circuiting that apparently occurs in the Veneta rock filter.

Normal removal efficiencies were obtained upon initial startup for both the pilot-scale filter and the full-scale filter. The lack of a lag period for obtaining normal removal efficiencies shows that the sedimentation removal mechanism does not depend upon development of the slime layer on the rocks or growth of any biological organisms. Therefore, rock filters probably can be used intermittently without any loss in performance.

## LONG TERM OPERATING CHARACTERISTICS

The analysis of influent and effluent characteristics for the Veneta rock filter demonstrates that the theoretical oxygen demand of particulate organic material removed from the lagoon effluent is much larger than the dissolved oxygen present for aerobic decomposition (see Table 7). The reduction in COD across the rock filter ranged from 15 to 116 mg/l (weekly averages) with a flow-weighted average of about 45 mg/l. Consequently, a major fraction of the organic material removed within the rock filter has to be simply stored.

Since much of the organic material removed is stored and not aerobically stabilized, a number of questions have been raised regarding the long-term operating characteristics of rock filters. These concerns include:

1. The potential plugging of rock filters with organic matter after a limited number of years in operation,

2. A progessive loss in efficiency due to buildup of organic matter on the rocks and subsequent short circuiting,

3. The development of odorous conditions or large soluble organic materials in the effluent due to anaerobic decomposition of the stored organic material, and

4. The possible practicality of cleaning the rock bed if undesirable conditions develop.

These concerns are addressed in order below.

It is possible to estimate the rate at which solids accumulate in a rock filter and, subsequently, its useful life. This rate will depend primarily on lagoon effluent quality, removal efficiency, and DO in the lagoon effluent. For the Veneta rock filter, the suspended solids removed in the rock filter are 7900 kg/yr based upon average flows of 264,000 $m^3$/yr and average removals of 30 mg/l of TSS. If the oxygen equivalent of the cells is 1.5 mg COD/mg TSS, the potential aerobic decomposition based on an influent DO of 10 mg/l is

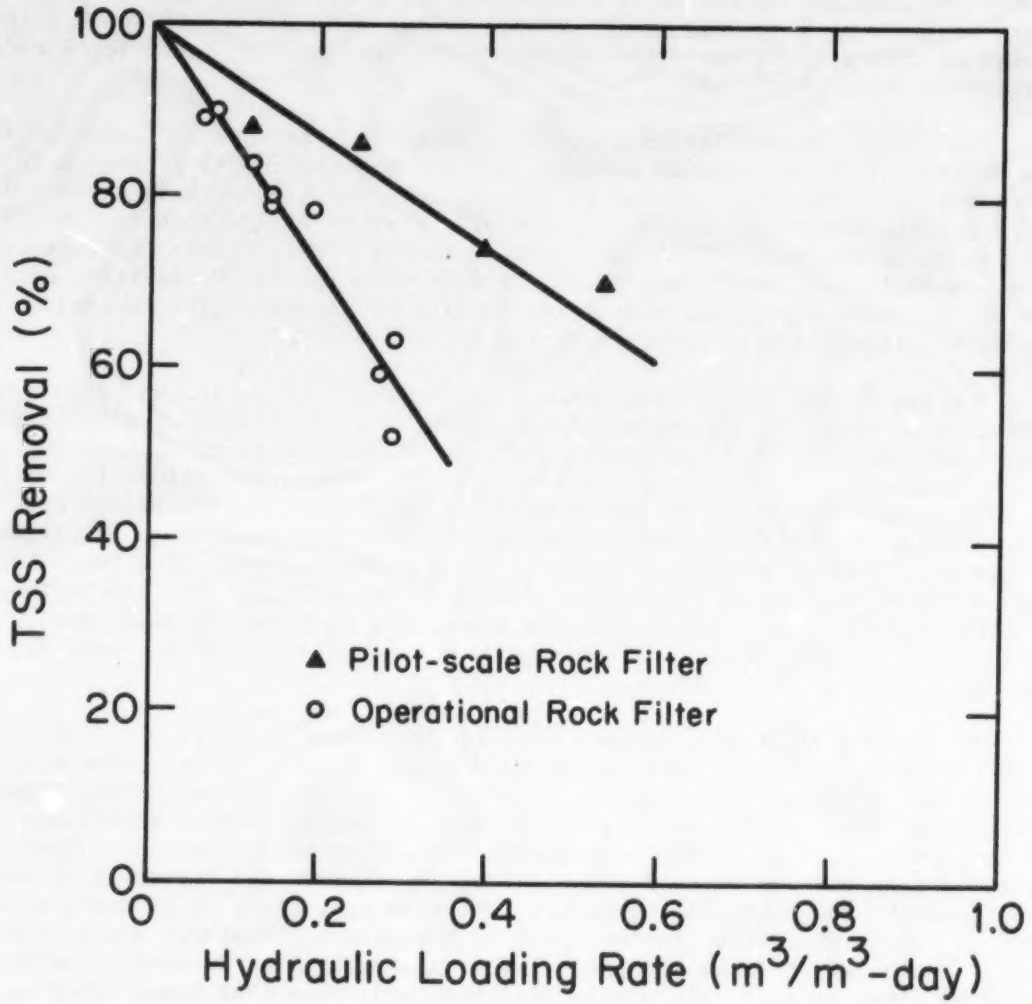


Figure 21. Comparison of pilot-scale and full-scale rock filter.

1760 kg/yr which means 6160 kg/yr of TSS are stored. If this material is 20 percent solids (26), then the volume occupied by this stored organic material is 31 $m^3$/yr. The Veneta rock filter void volume is 3400 $m^3$ and thus the useful life of the rock filter, assuming 50 percent of the voids can be filled with TSS, is 55 years. Consequently, possible plugging of the Veneta rock filter bed does not appear to be a problem. It should be recognized that the above estimate applies only to the Veneta filter with the assumptions listed. Design of rock filters for other locations requires that an estimate be made based upon local conditions.

The second concern listed involves a possible loss in efficiency due to the buildup of stored organic matter. The mathematical model presented in Section 6 indicates that removal efficiency is a function of $\theta/d_s$ where $\theta$ is the hydraulic detention time and $d_s$, the effective settling distance. While filling in of the void volume with organic material will reduce the detention time, it will also result in a proportionate reduction in the settling distance. Therefore, according to the model, the buildup of stored organic material should not significantly affect the removal efficiency.

The third concern was that anaerobic decomposition of stored organic material would result in objectionable sulfide odors or release of soluble organic material. During this study, the Veneta rock filter did not exhibit any tendency to release soluble organic material. Effluent BOD values indicated a proportionate reduction to TSS removals (Figure 17) and soluble COD analyses indicated no significant change occurred in passing through the rock filter (Table 7). Sulfide generation occurred to a limited extent (detectable by odor only) during the winter months (February through May, 1977 and beginning November, 1978). The sulfide odor was detectable only in the immediate vicinity of the rock filter effluent manhole during those months, however, and was not a significant problem.

It is postulated that several factors functioned to limit the firm establishment of an anaerobic zone in the Veneta rock filter. First, anaerobic degradation rates for algal residues are very slow and the refractory organic fraction is high (20-40 percent) (27). Second, large, diurnal variations in DO and pH are typical in the lagoon effluent during summer months. These variations in DO tend to send pulses of oxygen through the filter which probably inhibits the anaerobic bacteria. The wide variations in pH would also tend to reduce anaerobic growth. Lastly, the cold temperatures during the winter months would limit the growth rate and survival of anaerobic bacteria. Based on these factors, it appears that the conditions that would favor anaerobic degradation are warm temperatures and low DO due to lack of photosynthetic activity. These two factors generally do not occur simultaneously, but the possibility of developing anaerobic conditions within a rock filter should be evaluated based on local conditions.

The final concern listed regards whether cleaning of the rock bed is practical or necessary. Based on the discussion above, it does not appear that cleaning will be necessary, at least, for the Veneta rock filter. Furthermore, it does not appear that any mechanical methods for cleaning methods for cleaning, short of physical removal of the rocks and washing, will be practical. As discussed earlier, the gelatinous organic slime layer that

forms on the rocks is not easily removed. Flushing has been suggested, but the flow rates required to produce turbulent hydraulic shear capable of removing the slime layer would be orders of magnitude greater than normal hydraulic loadings. Air injection into the bottom of the rock filter to create shearing turbulence has also been suggested, but effective removal would require installation of an extensive network of air piping and diffusers and provisions for a blower.

A practice at Veneta that apparently serves to limit the extent of the slime layer and delay any anaerobic activity is draining of the rock filter during the summer, dry weather period when effluent is not being discharged. Excavation and investigation of the rocks in the filter bed during the summer of 1978, approximately one month after it had been drained for the summer dry-weather period, revealed that the slime layer on the rocks had completely dried out, leaving a thin layer of dried organic material. Consequently, the draining and drying of rock filters may offer a means to reduce the volume occupied by the stored organic material and limit the permanent establishment of an anaerobic zone.

An additional alternative where continuous discharge may not be permitted or required is to establish a closed loop reaeration scheme. During periods of non-discharge, liquid from the rock filter could be recycled through an aerator and pumped back to the rock filter. With a relatively large flow rate, sufficient oxygen could be supplied to the rock filter to aerobically stabilize the stored organic material in a relatively short time (typical non-discharge time is 2 to 3 months out of the year).

## ROCK FILTER DESIGN

A primary objective of this study was to establish engineering design criteria for utilization of rock filters in other locations.

### Design Basis

Within this report, a mathematical model of rock filter settling was developed based on algal settling rates, wastewater constituent data for the Veneta rock filter was empirically analyzed, and a pilot-scale rock filter was evaluated and compared to a full-scale operating facility. These results suggest three possible methods for determining appropriate design loadings:

1. Pilot Testing. Pilot-scale experiments at Veneta indicated that removal efficiencies could be predicted based on pilot-scale results. A comparison of the theoretical versus actual hydraulic detention time in the pilot-scale filter should be evaluated against the probable effectiveness of flow distribution in the full-scale system. The pilot-scale system should be monitored (at best intermittently) for a minimum of one year to analyze performance when different algal species are dominant in the lagoon.

2. Algal Settling Rates. At the beginning of this study, it was envisioned that fluoremetric measurement of algal settling rates coupled with the theoretical framework of the mathematical model

would provide a low-cost, rational method for the design of rock filters. During this study, however, several limitations of the fluorometric settling test were discovered:

a) Accurate measurements of settling velocities in the range of those found for lagoon effluents (less than 0.1 m/day) is very difficult. Furthermore, definition of the distribution of settling velocities requires following the fluorometric trace to near zero reading, which may take several days. The error associated with such long-term measurements could be very large.

b) Blue-green algae rise; consequently, the fluorometer must be designed to measure rising rates as well as sinking rates, even simultaneously. This presents complications to rapid measurement and the interpretation of results.

c) Flagellates and blue-green algae will respond to light. The extent to which the light from the fluorometer lamp affects the settling or rising behavior of these algae is not known.

Consequently, the use of fluorometrically measured algal settling rates cannot be recommended as a basis for design at present. Future improvements in the method, however, may allow its use as a design basis.

3. Empirical Design. Pilot testing may not be practical for all locations, particularly for very small lagoons. An empirical design is possible based on the results of this study. The TSS removal curve shown in Figure 16, with the 90% prediction limits, could be used as an empirical design curve. The EPA has generally accepted 90% prediction limits as corresponding to a 30 consecutive day average (40 CFR 133 and 43 FR 53161).

In utilizing such an empirical approach, it is assumed that the settling rates of algae in the lagoon to be upgraded are similar to those observed during this study. The validity of this assumption is unknown at present. The measurement of algal settling rates, though they may be only approximate, could serve to test the validity of this assumption. Also, identification of dominant algal species during various seasons of the year could be useful.

Application of a safety factor to empirical designs would be appropriate to account for the possibility of slower settling algal cultures. It should also be recognized that improvements in flow distribution over the Veneta rock filter design could result in a smaller required volume.

## Other Design Criteria

The results of this study have suggested several other important design considerations for rock filters. First, the water surface in the rock filter should not be exposed to sunlight to prevent regrowth of algae. The use of

covered effluent weirs and an extra 0.3 m (1.0 ft) of rock media above the water surface at Veneta was effective in preventing regrowth of algae. Second, rock filter systems should be designed for possible generation of sulfides. Effluent piping should be completely enclosed and reaeration minimized prior to chlorination. Chlorination facility design should allow for larger doses to oxidize sulfides. Third, provisions for draining and drying of the rock filter should be included. Fourth, rock filter effluent will generally be depleted in DO. Where required, the effluent stream should be aerated prior to discharge. Fifth, designs should allow for control of flow rates to the rock filter. Together with proper use of lagoon storage capacities, adjustment of the hydraulic loading applied to the rock filter is the most effective operating tool available to meet strict discharge standards.

## Flow Scheme

Rock filters should be designed as horizontal, plug-flow basins. The use of a vertical flow scheme would allow rising algae (blue-greens) to escape in the effluent. As indicated by the pilot test results, hydraulic short circuiting or poor flow distribution will have a direct negative impact on removal efficiency.

## Rock Size

Definition of rock size to be used in the rock filter is a compromise between volumetric removal efficiency and potential plugging problems. The use of smaller rocks will reduce the settling distance within the rock filter and therefore, increase volumetric efficiency. However, the dangers of plugging are increased.

The rock size used at Veneta (7.6 to 15.2 cm or 3 to 6 in) appears to be a reasonable compromise. The use of smaller rocks is not recommended without extensive pilot testing to evaluate the potential for plugging.

## Cost

The Veneta rock filter was constructed in 1975 for a total cost of approximately $66,000. This cost included all site work and excavation, the rock media, influent and effluent piping and weirs, and the feed pump. This cost was approximately 25 percent of the total lagoon expansion cost, which included essentially all the present facilities except the smaller, second lagoon.

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APPENDIX A

TABLE A-1. ANALYTICAL DATA FOR VENETA ROCK FILTER

| Date | Flow Rate ($m^3$/day) | Temperature (°C) | | pH*** | | DO*** (mg/l) | | TSS (mg/l) | | TVSS (% of TSS) | | $BOD_5$ (mg/l) | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | I* | E** | I | E | I | E | I | E | I | E | I | E |
| 11/13/77 | 1100 | 9 | 10 | 9.1 | 7.4 | 11.0 | 5.0 | 44 | 13 | 61 | 72 | 18 | 10 |
| 11/14/77 | 1100 | 10 | 10 | 8.9 | 7.5 | 8.5 | 4.8 | 43 | 9 | 75 | 98 | 17 | 9 |
| 11/15/77 | 1100 | 11 | 11 | 8.9 | 7.8 | 7.6 | 4.3 | 38 | 9 | 76 | 77 | 17 | 7 |
| 11/16/77 | 1100 | 9 | 9 | 9.0 | 7.7 | 9.1 | 4.2 | 39 | 8 | 94 | 90 | 18 | 7 |
| 11/17/77 | 1060 | 8 | 8 | 9.1 | 7.8 | 11.9 | 4.4 | 49 | 10 | 88 | 85 | 19 | 8 |
| 11/18/77 | 1140 | 7 | 7 | 9.0 | 7.8 | 10.4 | 4.7 | 42 | 8 | 91 | 100 | 28 | 9 |
| 11/19/77 | 1210 | 5 | 5 | 9.0 | 7.7 | 12.2 | 4.3 | 37 | 10 | 98 | 98 | 25 | 10 |
| wk. avg. | 1120 | 8.4 | 8.6 | 9.0 | 7.7 | 10.1 | 4.5 | 42 | 9 | 83 | 89 | 20 | 9 |
| 1/01/78 | 2270 | 4 | 4 | 9.0 | 7.1 | 16.5 | 5.3 | 30 | 13 | 92 | 89 | 30 | 17 |
| 1/02/78 | 2310 | 2 | 3 | 8.8 | 7.1 | 15.3 | 5.1 | 28 | 15 | 93 | 92 | 27 | 16 |
| 1/03/78 | 2310 | 6 | 5 | - | - | 16.0 | 6.3 | 30 | 14 | 90 | 92 | 28 | 14 |
| 1/04/78 | 2310 | 6 | 6 | - | - | 16.2 | 5.2 | 32 | 15 | 89 | 90 | 27 | 13 |
| 1/05/78 | 2270 | 8 | 8 | 8.5 | 7.2 | 14.0 | 5.3 | 30 | 14 | 90 | 82 | 26 | 12 |
| 1/06/78 | 2270 | 9 | 9 | 8.6 | 7.0 | 15.1 | 6.4 | 30 | - | 89 | - | 28 | 12 |
| 1/07/78 | 570 | 7 | 9 | 7.9 | 7.3 | 14.3 | 10.1 | 26 | 14 | 89 | 86 | 26 | 14 |
| wk. avg. | 2040 | 6.0 | 6.3 | 8.6 | 7.1 | 15.4 | 6.2 | 29 | 14 | 90 | 89 | 27 | 14 |
| 2/05/78 | 2270 | 10 | 10 | 7.4 | 7.2 | 8.2 | 3.7 | 21 | 10 | 95 | 95 | 18 | 12 |
| 2/06/78 | 2270 | 10 | 10 | 7.3 | 7.0 | 9.1 | 3.2 | 24 | 6 | 92 | 84 | 21 | 8 |
| 2/07/78 | 2230 | 10 | 10 | 8.2 | 7.2 | 12.2 | 3.0 | 26 | 10 | 82 | 78 | 18 | 9 |
| 2/08/78 | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 2/09/78 | 2270 | 9 | 8 | 7.5 | 7.2 | 10.3 | 3.1 | 33 | 10 | 88 | 84 | 21 | 10 |
| 2/10/78 | 2270 | 8 | 8 | 7.5 | 7.0 | 14.0 | 3.4 | 31 | 12 | 90 | 84 | 21 | 10 |
| 2/11/78 | 2230 | 9 | 8 | - | - | 13.2 | 2.8 | 35 | 12 | 91 | 88 | 22 | 10 |
| wk. avg. | 2260 | 9.3 | 9.0 | 7.6 | 7.1 | 11.2 | 3.2 | 28 | 10 | 90 | 86 | 20 | 10 |

*I = Rock filter influent (lagoon effluent)
**E = Rock filter effluent
***Grab sample measurement, diurnal variations may cause apparent day to day fluctuations.

(continued)

TABLE A-1. (Continued)

| Date | Soluble COD (mg/l) I | Soluble COD (mg/l) E | Total COD (mg/l) I | Total COD (mg/l) E | TOC (mg/l) I | TOC (mg/l) E | $NH_4^+$-N (mg/l) I | $NH_4^+$-N (mg/l) E | Org-N (mg/l) I | Org-N (mg/l) E | $NO_3^-$-N (mg/l) I | $NO_3^-$-N (mg/l) E | Soluble P (mg/l) I | Soluble P (mg/l) E |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 11/13/77 | | | 122 | 88 | 34 | 29 | 1.0 | 1.8 | 3.2 | 2.2 | 1.5 | 3.7 | 4.9 | 3.8 |
| 11/14/77 | | | 125 | 80 | 38 | 30 | 1.3 | 2.4 | 3.4 | 5.4 | 1.2 | 2.8 | 5.4 | 4.6 |
| 11/15/77 | | | 125 | 78 | 37 | 30 | 1.4 | 2.4 | 8.3 | 4.1 | 1.7 | 2.0 | 5.5 | 4.4 |
| 11/16/77 | | | 122 | 74 | 38 | 28 | 0.7 | 1.5 | 4.1 | 2.2 | 2.0 | 2.3 | 4.2 | 3.8 |
| 11/17/77 | | | 118 | 73 | 38 | 27 | 0.5 | 1.5 | 3.0 | 3.7 | 0.8 | 1.5 | 5.4 | 4.6 |
| 11/18/77 | | | 118 | 73 | 38 | 27 | 0.5 | 1.6 | 4.6 | 2.7 | 1.3 | 1.2 | 4.2 | 3.3 |
| 11/19/77 | | | 115 | 71 | 35 | 27 | 0.3 | 0.8 | 1.9 | 3.2 | 1.8 | 1.5 | 4.0 | 2.7 |
| wk. avg. | | | 121 | 77 | 37 | 28 | 0.8 | 1.7 | 4.1 | 3.4 | 1.5 | 2.1 | 4.8 | 3.9 |
| 1/01/78 | | | 68 | 56 | 25 | 16 | 2.1 | 2.4 | 10.5 | 11.7 | 0.7 | 1.4 | 1.9 | 1.6 |
| 1/02/78 | | | 70 | 39 | 23 | 18 | 2.7 | 3.3 | 4.7 | 8.1 | 1.2 | 1.7 | - | - |
| 1/03/78 | | | 65 | 44 | 22 | 15 | 3.1 | 2.9 | 6.7 | 3.6 | 0.8 | 1.8 | - | - |
| 1/04/78 | | | 64 | 44 | 22 | 15 | 3.1 | 2.6 | 2.7 | 5.8 | 1.3 | 1.7 | - | - |
| 1/05/78 | | | 64 | 48 | 20 | 17 | 3.2 | 2.6 | - | - | 1.2 | 1.8 | 1.7 | 2.3 |
| 1/06/78 | | | 67 | 42 | 26 | 14 | 5.3 | 3.6 | 3.9 | 1.5 | 0.9 | 1.5 | 1.6 | 1.3 |
| 1/07/78 | | | 72 | 42 | 28 | - | 5.3 | 3.2 | 6.3 | 1.4 | 1.1 | 1.3 | 1.5 | 1.2 |
| wk. avg. | | | 67 | 45 | 24 | 16 | 3.5 | 2.9 | 5.8 | 5.4 | 1.0 | 1.6 | 1.7 | 1.6 |
| 2/05/78 | 26 | 27 | 44 | 47 | 18 | - | 14.9 | 11.8 | 3.2 | 1.7 | 1.1 | 1.1 | 2.7 | 2.1 |
| 2/06/78 | 26 | 28 | 51 | 32 | 20 | 13 | 17.6 | 14.9 | 6.5 | 3.1 | 0.9 | 1.2 | 2.2 | - |
| 2/07/78 | 21 | 23 | 48 | 33 | 17 | 13 | 14.9 | 11.0 | 6.3 | 1.4 | 0.8 | 1.1 | 2.1 | 2.7 |
| 2/08/78 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 2/09/78 | 23 | 34 | 56 | 34 | 20 | 13 | 14.7 | 11.7 | 5.6 | 0.0 | 0.7 | 1.1 | 2.3 | 2.8 |
| 2/10/78 | 21 | 22 | 51 | 37 | - | 14 | - | - | 7.3 | 1.4 | - | - | 3.7 | 3.1 |
| 2/11/78 | 20 | 25 | 54 | 33 | 20 | 13 | - | - | 5.3 | 0.8 | 0.7 | 0.8 | 2.2 | 2.3 |
| wk. avg. | 23 | 26 | 51 | 36 | 19 | 13 | 15.5 | 12.4 | 5.7 | 1.4 | 0.8 | 1.1 | 2.5 | 2.6 |

(continued)

TABLE A-1. (Continued)

| Date | Total P (mg/l) | | Chlorophyll a (mg/l) | | Chlorophyll b (mg/l) | | Chlorophyll c (mg/l) | | Sulfides (mg/l) | |
|---|---|---|---|---|---|---|---|---|---|---|
| | I | E | I | E | I | E | I | E | I | E |
| 11/13/77 | 5.6 | 4.0 | | | | | | | ND[3] | ND |
| 11/14/77 | 5.4 | 4.4 | | | | | | | ND | ND |
| 11/15/77 | 5.5 | 4.4 | | | | | | | ND | ND |
| 11/16/77 | 5.0 | 4.4 | | | | | | | ND | ND |
| 11/17/77 | 5.9 | 4.4 | | | | | | | ND | ND |
| 11/18/77 | 4.9 | 4.0 | | | | | | | ND | ND |
| 11/19/77 | 4.4 | 2.9 | | | | | | | ND | ND |
| wk. avg. | 5.2 | 4.1 | | | | | | | ND | ND |
| 1/01/78 | 2.3 | 1.9 | 421 | 170 | 65 | 32 | 36 | 24 | ND | ND |
| 1/02/78 | - | - | 356 | 210 | 46 | 34 | 32 | 36 | ND | ND |
| 1/03/78 | - | - | 318 | 124 | 33 | 10 | 21 | 0 | ND | ND |
| 1/04/78 | - | - | 338 | - | 45 | - | 37 | - | ND | ND |
| 1/05/78 | 2.7 | 1.7 | 294 | 195 | 33 | 34 | 12 | 28 | ND | ND |
| 1/06/78 | 1.8 | 1.5 | 289 | 104 | 28 | 8 | 7 | 0 | ND | ND |
| 1/07/78 | 1.6 | 1.4 | 336 | 156 | 26 | 19 | 13 | 0 | ND | ND |
| wk. avg. | 2.1 | 1.6 | 336 | 160 | 39 | 23 | 23 | 15 | ND | ND |
| 2/05/78 | 5.0 | 5.7 | 128 | 30 | 15 | 7 | 0 | 0 | ND | - |
| 2/06/78 | 3.0 | 2.6 | 252 | 36 | 44 | 5 | 0 | 4 | ND | <0.1 |
| 2/07/78 | 2.7 | 3.7 | 198 | 52 | 43 | 8 | 40 | 0 | ND | <0.1 |
| 2/08/78 | - | - | - | - | - | - | - | - | - | - |
| 2/09/78 | 3.6 | 3.7 | 298 | 84 | 75 | 22 | 40 | 10 | ND | <0.1 |
| 2/10/78 | 2.7 | 2.6 | 323 | 109 | 83 | 16 | 43 | 0 | ND | <0.1 |
| 2/11/78 | 2.2 | 2.3 | 367 | 118 | 93 | 31 | 49 | 20 | ND | <0.1 |
| wk. avg. | 3.2 | 3.4 | 261 | 72 | 59 | 15 | 29 | 6 | ND | <0.1 |

[3]ND = Not detectable (<<0.1 mg/l)

TABLE A-2. ANALYTICAL DATA FOR VENETA ROCK FILTER

| Date | Flow Rate ($m^3$/day) | Temperature (°C) | | PH | | DO (mg/1) | | TSS (mg/1) | | TVSS (% of TSS) | | $BOD_5$ (mg/1) | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | I | E | I | E | I | E | I | E | I | E | I | E |
| 3/05/78 | 2270 | 10 | 10 | 8.5 | 7.1 | 15.3 | 3.3 | 28 | 9 | 88 | 85 | 26 | 15 |
| 3/06/78 | 2270 | 11 | 10 | 8.0 | 7.1 | 13.7 | 2.8 | 22 | 14 | 88 | 84 | 19 | 14 |
| 3/07/78 | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 3/08/78 | 2230 | 11 | 10 | - | - | 8.4 | 3.0 | 19 | 8 | 87 | 83 | 20 | 13 |
| 3/09/78 | 2230 | 11 | 10 | 7.3 | 7.0 | 7.1 | 3.0 | 23 | 8 | 93 | 92 | 21 | 14 |
| 3/10/78 | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 3/11/78 | 2230 | 10 | 9 | - | - | 9.4 | 2.9 | 20 | 8 | 90 | 85 | 21 | 18 |
| wk. avg. | 2250 | 10.6 | 9.8 | 7.9 | 7.1 | 10.8 | 3.0 | 22 | 9 | 89 | 86 | 21 | 15 |
| 4/16/78 | 490 | 13 | 13 | 7.4 | 7.2 | 8.5 | 3.8 | 44 | 7 | 91 | 66 | 40 | 20 |
| 4/17/78 | 1140 | 12 | 11 | 9.1 | 7.2 | 13.3 | 3.8 | 40 | 5 | 92 | 73 | 42 | 29 |
| 4/18/78 | 1140 | 14 | 13 | 8.8 | 7.3 | 10.2 | 2.6 | 47 | 6 | 91 | 95 | 31 | 15 |
| 4/19/78 | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 4/20/78 | 1100 | 12 | 11 | 9.0 | 7.2 | 11.2 | 2.9 | 46 | 9 | 90 | 30 | 38 | 17 |
| 4/21/78 | 1100 | 12 | 11 | 9.0 | 7.2 | 11.9 | 2.9 | 50 | 7 | 93 | 71 | 37 | 19 |
| 4/22/78 | 1100 | 11 | 10 | 9.0 | 7.3 | 10.0 | 3.2 | 38 | 8 | 95 | 60 | 44 | 13 |
| wk. avg. | 1020 | 12.3 | 11.5 | 8.7 | 7.2 | 10.8 | 3.2 | 44 | 7 | 92 | 66 | 39 | 19 |
| 5/14/78 | 1100 | 15 | 14 | - | - | 14.2 | 3.0 | 33 | 8 | 90 | 92 | 49 | 22 |
| 5/15/78 | 1100 | 15 | 14 | 9.6 | 7.2 | 16.6 | 4.3 | 36 | 9 | 87 | 89 | 42 | 20 |
| 5/16/78 | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 5/17/78 | 1100 | 16 | 16 | 9.4 | 7.2 | 13.0 | 3.0 | 38 | 7 | 83 | 79 | 30 | 16 |
| 5/18/78 | 1590 | 19 | 17 | 10.0 | 7.3 | 19.6 | 2.9 | 42 | 8 | 83 | 83 | 38 | 16 |
| 5/19/78 | 1590 | 21 | 19 | 10.3 | 7.4 | 22.0 | 2.4 | 50 | 9 | 80 | 84 | 44 | 18 |
| 5/20/78 | 1590 | 23 | 22 | 10.3 | 7.5 | 18.8 | 2.0 | 61 | 11 | 83 | 83 | 51 | 19 |
| wk. avg. | 1360 | 18.2 | 17.0 | 9.9 | 7.3 | 17.4 | 2.9 | 43 | 9 | 84 | 85 | 42 | 18 |

(continued)

TABLE A-2. (Continued)

| Date | Soluble COD (mg/l) I | Soluble COD (mg/l) E | Total COD (mg/l) I | Total COD (mg/l) E | TOC (mg/l) I | TOC (mg/l) E | $NH_4^+$-N (mg/l) I | $NH_4^+$-N (mg/l) E | Org-N (mg/l) I | Org-N (mg/l) E | $NO_3^-$-N (mg/l) I | $NO_3^-$-N (mg/l) E | Soluble P (mg/l) I | Soluble P (mg/l) E |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 3/05/78 | | | 62 | 39 | 25 | 15 | 12.7 | 12.7 | 5.0 | 4.5 | 1.2 | 1.3 | 2.6 | 2.7 |
| 3/06/78 | | | 66 | 50 | 26 | 17 | 16.3 | 13.8 | 5.0 | 2.5 | 1.2 | 0.9 | 1.6 | 1.7 |
| 3/07/78 | | | - | - | - | - | - | - | - | - | - | - | - | - |
| 3/08/78 | | | 56 | 39 | 20 | - | 17.9 | 15.0 | 1.8 | 3.8 | 0.8 | 0.6 | 2.1 | 2.6 |
| 3/09/78 | | | 68 | 48 | 21 | 15 | 17.7 | 15.0 | 4.5 | 3.0 | 1.0 | 0.6 | 2.9 | 5.0 |
| 3/10/78 | | | - | - | - | - | - | - | - | - | - | - | - | - |
| 3/11/78 | | | 55 | 46 | 21 | 16 | 15.0 | 15.0 | 3.2 | 2.5 | 1.4 | 0.7 | 1.5 | 5.8 |
| wk. avg. | | | 61 | 44 | 23 | 16 | 15.9 | 14.3 | 3.9 | 3.3 | 1.1 | 0.8 | 2.1 | 3.5 |
| 4/16/78 | | | 134 | 79 | | | 4.0 | 4.9 | 8.2 | 3.9 | 2.1 | 1.7 | 5.0 | - |
| 4/17/78 | | | 143 | 77 | | | 3.1 | 6.4 | 6.6 | 3.2 | 1.5 | 1.7 | 7.4 | 5.9 |
| 4/18/78 | | | 143 | 73 | | | 5.1 | 5.2 | 10.1 | 6.0 | 1.6 | 1.4 | 5.6 | 5.0 |
| 4/19/78 | | | - | - | | | - | - | - | - | - | - | - | - |
| 4/20/78 | | | 150 | 82 | | | 4.5 | 5.7 | 9.0 | 4.9 | 1.7 | 1.6 | 9.7 | 5.3 |
| 4/21/78 | | | 163 | 85 | | | 2.6 | 5.2 | 9.6 | 4.4 | 1.6 | 1.3 | 4.1 | 3.9 |
| 4/22/78 | | | 150 | - | | | 3.6 | 5.4 | 9.5 | 4.5 | 1.9 | 1.6 | 4.3 | 3.1 |
| wk. avg. | | | 147 | 80 | | | 3.8 | 5.5 | 8.8 | 4.5 | 1.7 | 1.5 | 6.0 | 4.6 |
| 5/14/78 | | | 146 | 101 | 55 | 41 | 6.3 | 7.5 | 8.8 | 5.7 | - | - | 4.8 | - |
| 5/15/78 | | | 151 | 101 | 51 | 40 | 3.5 | 6.6 | 9.5 | 6.0 | 1.3 | 0.8 | 6.1 | 5.2 |
| 5/16/78 | | | - | - | - | - | - | - | - | - | - | - | - | - |
| 5/17/78 | | | 174 | 99 | 50 | - | 3.5 | 7.6 | 8.1 | 6.3 | 1.7 | 1.0 | 3.5 | 5.4 |
| 5/18/78 | | | 156 | 105 | 52 | 39 | 2.6 | 8.8 | 7.3 | 4.4 | 2.0 | 1.1 | 3.1 | 5.0 |
| 5/19/78 | | | 154 | 105 | 66 | 40 | 1.7 | 7.2 | 7.7 | 4.3 | 2.6 | 1.3 | 2.6 | 5.0 |
| 5/20/78 | | | 173 | 111 | 61 | 37 | 1.6 | 6.0 | 9.1 | 4.3 | 3.7 | 1.0 | 2.7 | 3.7 |
| wk. avg. | | | 159 | 104 | 56 | 39 | 2.6 | 7.2 | 8.4 | 5.2 | 2.3 | 1.0 | 3.7 | 4.9 |

(continued)

TABLE A-2. (Continued)

| Date | Total P (mg/l) | | Chlorophyll a (mg/l) | | Chlorophyll b (mg/l) | | Chlorophyll c (mg/l) | | Sulfides (mg/l) | |
|---|---|---|---|---|---|---|---|---|---|---|
| | I | E | I | E | I | E | I | E | I | E |
| 3/05/78 | 2.9 | 2.7 | 242 | 46 | 35 | 2 | 34 | 2 | ND | <0.1 |
| 3/06/78 | 3.0 | 2.9 | 177 | 44 | 28 | 3 | 35 | 9 | ND | <0.1 |
| 3/07/78 | - | - | - | - | - | - | - | - | - | - |
| 3/08/78 | 2.3 | 2.3 | 132 | 28 | 17 | 7 | 24 | 16 | ND | <0.1 |
| 3/09/78 | 3.0 | 2.0 | 119 | 24 | 0 | 5 | 0 | 0 | ND | <0.1 |
| 3/10/78 | - | - | - | - | - | - | - | - | - | - |
| 3/11/78 | 2.4 | 5.5 | 137 | 18 | 7 | 0 | 0 | 0 | ND | <0.1 |
| wk. avg. | 2.7 | 3.1 | 161 | 32 | 17 | 3 | 19 | 5 | ND | <0.1 |
| 4/16/78 | 5.7 | 5.7 | 454 | 20 | 230 | 20 | 119 | 27 | ND | ND |
| 4/17/78 | 8.1 | 5.0 | 821 | 9 | 422 | 9 | 203 | 18 | ND | ND |
| 4/18/78 | 8.2 | 7.1 | 587 | 6 | 320 | 6 | 126 | 9 | ND | ND |
| 4/19/78 | - | - | - | - | - | - | - | - | - | - |
| 4/20/78 | 7.9 | 3.2 | 602 | 13 | 307 | 8 | 117 | 9 | ND | ND |
| 4/21/78 | 5.4 | 4.1 | 935 | 14 | 514 | 14 | 132 | 31 | ND | ND |
| 4/22/78 | 5.2 | 5.0 | 727 | 16 | 292 | 15 | 192 | 35 | ND | ND |
| wk. avg. | 6.8 | 5.0 | 688 | 13 | 348 | 12 | 148 | 22 | ND | ND |
| 5/14/78 | 5.0 | 5.2 | 152 | 18 | 175 | 26 | 254 | 57 | ND | ND |
| 5/15/78 | 5.9 | 5.9 | 195 | 23 | 222 | 28 | 351 | 60 | ND | ND |
| 5/16/78 | - | - | - | - | - | - | - | - | - | - |
| 5/17/78 | 5.7 | 5.6 | 197 | 22 | 233 | 29 | 351 | 62 | ND | ND |
| 5/18/78 | 5.9 | 5.9 | 231 | 33 | 272 | 40 | 410 | 77 | ND | ND |
| 5/19/78 | 5.0 | 4.4 | 262 | 48 | 277 | 44 | 509 | 99 | ND | ND |
| 5/20/78 | 5.9 | 5.2 | - | 63 | - | 63 | - | 93 | ND | ND |
| wk. avg. | 5.6 | 5.4 | 207 | 34 | 236 | 38 | 375 | 75 | ND | ND |

TABLE A-3. ANALYTICAL DATA FOR VENETA ROCK FILTER

| Date | Flow Rate ($m^3$/day) | Temperature (°C) | | pH | | DO (mg/l) | | TSS (mg/l) | | TVSS (% of TSS) | | $BOD_5$ (mg/l) | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | I | E | I | E | I | E | I | E | I | E | I | E |
| 7/30/78 | 530 | 22 | 21 | 9.4 | 7.4 | - | - | 105 | 10 | 87 | 70 | 49 | 16 |
| 7/31/78 | 530 | - | - | 9.4 | 7.4 | - | - | 119 | 10 | 90 | 76 | - | 13 |
| 8/01/78 | 570 | 21 | 21 | 9.7 | 7.6 | 6.8 | 3.2 | 105 | 11 | 89 | 67 | 50 | 10 |
| 8/02/78 | 570 | 22 | 22 | 10.0 | 7.8 | 7.6 | 1.9 | 97 | 11 | 89 | 70 | 43 | 9 |
| 8/03/78 | 570 | 22 | 20 | 9.7 | 7.7 | 7.3 | 1.0 | 107 | 8 | 85 | 62 | 49 | 15 |
| 8/04/78 | 610 | 22 | 20 | 9.8 | 7.6 | 7.2 | 2.3 | 101 | 13 | 86 | 61 | 44 | 9 |
| 8/05/78 | 610 | 23 | 21 | 9.4 | 7.5 | 5.5 | 0.5* | 100 | 7 | 93 | 65 | 55 | 8 |
| wk. avg. | 570 | 22.0 | 20.8 | 9.6 | 7.6 | 6.9 | 1.8 | 105 | 10 | 88 | 67 | 48 | 11 |
| 9/17/78 | 530 | 16 | 14 | 9.2 | 7.5 | 7.3 | 1.0 | 73 | 4 | 79 | 38 | 52 | 10 |
| 9/18/78 | 530 | 15 | 17 | 9.2 | 7.4 | 7.8 | 2.8 | 88 | 12 | - | 60 | 57 | 17 |
| 9/19/78 | 530 | 14 | 14 | - | - | 4.5 | 3.5 | 71 | 3 | 93 | 70 | 58 | 17 |
| 9/20/78 | 570 | 12 | 11 | - | - | 7.5 | 5.4 | 93 | 18 | 89 | - | 58 | - |
| 9/21/78 | 530 | 15 | 15 | - | - | 3.7 | 2.5 | 108 | 10 | 87 | 77 | 58 | 14 |
| 9/22/78 | 530 | 15 | 11 | - | - | 7.6 | 0.2* | 77 | 12 | 90 | 80 | 55 | 16 |
| 9/23/78 | 530 | - | - | - | - | - | - | 76 | 18 | 86 | 70 | 52 | - |
| wk. avg. | 530 | 14.5 | 13.7 | 9.2 | 7.5 | 6.4 | 2.6 | 84 | 10 | 87 | 66 | 56 | 15 |
| 11/19/78 | 1100 | 8 | 7 | 8.0 | 7.5 | 10.3 | 4.0 | - | - | - | - | 42 | 27 |
| 11/20/78 | 1100 | 7 | 6 | - | - | 10.0 | 4.6 | - | - | - | - | 46 | 22 |
| 11/21/78 | 1100 | 5 | 5 | 7.5 | 7.1 | - | 4.8 | 50 | 15 | 72 | 70 | 40 | 21 |
| 11/22/78 | 1140 | 5 | 5 | 7.7 | 7.1 | 10.8 | - | 41 | 12 | 93 | 79 | 45 | 17 |
| 11/23/78 | 1100 | 5 | 4 | 7.1 | 7.2 | 9.0 | 4.4 | 41 | 10 | 84 | 74 | 46 | 16 |
| 11/24/78 | 1140 | 4 | 5 | 7.7 | 7.1 | 10.5 | - | 43 | 8 | 92 | 88 | 31 | 13 |
| 11/25/78 | 1100 | 5 | 6 | 7.4 | 7.1 | 10.8 | - | 63 | 8 | 93 | 88 | - | 15 |
| wk. avg. | 1110 | 5.6 | 5.4 | 7.6 | 7.2 | 10.2 | 4.5 | 48 | 11 | 87 | 80 | 42 | 19 |

*DO measurement taken below effluent weirs.

(continued)

TABLE A-3. (Continued)

| Date | Soluble COD (mg/l) I | E | Total COD (mg/l) I | E | TOC (mg/l) I | E | $NH_4^+$-N (mg/l) I | E | Org-N (mg/l) I | E | $NO_3^-$-N (mg/l) I | E | Soluble P (mg/l) I | E |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 7/30/78 | 82 | 68 | 188 | 85 | 86 | 40 | - | - | 16.0 | 9.8 | 2.0 | 1.2 | | |
| 7/31/78 | 53 | 71 | 190 | 86 | 76 | 30 | 0.1 | 2.9 | 15.6 | 6.3 | 2.0 | 1.4 | | |
| 8/01/78 | 70 | 65 | 190 | 79 | - | 37 | 0.3 | 3.1 | 14.2 | 6.1 | 2.5 | 1.0 | | |
| 8/02/78 | 79 | 73 | 188 | 93 | 69 | 44 | 0.3 | 3.6 | - | 4.0 | 2.2 | 1.4 | | |
| 8/03/78 | 62 | 86 | 175 | 108 | 55 | 37 | 0.1 | 3.8 | - | 5.1 | 2.4 | 1.3 | | |
| 8/04/78 | 73 | 83 | 164 | 96 | 55 | 42 | 0.1 | 3.9 | - | 5.8 | 1.3 | 0.8 | | |
| 8/05/78 | 84 | 84 | 188 | 84 | 72 | 37 | 0.1 | 3.6 | - | 8.2 | 1.2 | 1.0 | | |
| wk. avg. | 72 | 76 | 183 | 90 | 69 | 38 | 0.2 | 3.5 | 15.3 | 6.5 | 1.9 | 1.2 | | |
| 9/17/78 | 85 | 106 | 196 | 80 | 92 | 21 | 2.1 | 4.4 | 15.4 | 4.4 | 1.1 | 0.9 | | |
| 9/18/78 | 96 | 80 | 212 | 87 | 72 | 27 | 1.4 | 4.9 | 24.4 | 7.3 | 1.6 | 1.4 | | |
| 9/19/78 | 99 | 88 | 201 | 95 | - | 28 | 2.1 | 4.2 | 12.1 | 5.4 | 1.7 | 1.3 | | |
| 9/20/78 | 114 | 71 | 211 | 93 | 59 | 24 | 1.7 | 4.6 | - | 5.0 | 1.5 | 0.8 | | |
| 9/21/78 | 104 | 93 | 204 | 82 | 50 | 32 | 2.0 | 4.7 | 15.6 | 5.2 | 1.0 | 0.5 | | |
| 9/22/78 | 94 | 78 | 196 | 79 | 64 | 51 | 1.8 | 5.0 | 13.8 | 6.8 | 0.9 | 0.6 | | |
| 9/23/78 | 95 | 51 | 184 | 82 | 47 | 44 | 1.6 | 4.7 | 13.8 | 7.5 | 0.8 | 1.0 | | |
| wk. avg. | 98 | 82 | 201 | 85 | 64 | 32 | 1.8 | 4.6 | 15.8 | 5.9 | 1.2 | 0.9 | | |
| 11/19/78 | - | - | 205 | 85 | | | 5.9 | 4.9 | | | 1.7 | 1.5 | | |
| 11/20/78 | 68 | 65 | 264 | 71 | | | 6.3 | 4.9 | | | 2.2 | 2.0 | | |
| 11/21/78 | 59 | 66 | 175 | 87 | | | 6.2 | 4.2 | | | 2.1 | 1.9 | | |
| 11/22/78 | 80 | 68 | 203 | 85 | | | 6.6 | 4.2 | | | 2.8 | 3.9 | | |
| 11/23/78 | 70 | 71 | 178 | 106 | | | 6.6 | 4.5 | | | 3.5 | 3.1 | | |
| 11/24/78 | 83 | 76 | 166 | 99 | | | 7.6 | 5.1 | | | 3.3 | 3.1 | | |
| 11/25/78 | 59 | 69 | 133 | 107 | | | 7.1 | 4.5 | | | 2.9 | 2.4 | | |
| wk. avg. | 70 | 69 | 189 | 91 | | | 6.6 | 4.6 | | | 2.6 | 2.6 | | |

(continued)

TABLE A-3. (Continued)

| Date | Total P (mg/l) I | Total P (mg/l) E | Chlorophyll a (mg/l) I | Chlorophyll a (mg/l) E | Chlorophyll b (mg/l) I | Chlorophyll b (mg/l) E | Chlorophyll c (mg/l) I | Chlorophyll c (mg/l) E | Sulfides (mg/l) I | Sulfides (mg/l) E |
|---|---|---|---|---|---|---|---|---|---|---|
| 7/30/78 | | | 218 | 20 | 146 | 19 | 83 | 34 | ND | ND |
| 7/31/78 | | | 358 | 18 | 217 | 22 | 326 | 44 | ND | ND |
| 8/01/78 | | | 213 | 20 | 110 | 25 | 251 | 53 | ND | ND |
| 8/02/78 | | | 202 | 20 | 162 | 28 | 124 | 72 | ND | ND |
| 8/03/78 | | | 189 | 9 | 148 | 13 | 117 | 32 | ND | ND |
| 8/04/78 | | | 194 | 9 | 127 | 11 | 102 | 16 | ND | ND |
| 8/05/78 | | | 265 | 7 | 180 | 10 | 155 | 22 | ND | ND |
| wk. avg. | | | 234 | 15 | 156 | 18 | 165 | 39 | ND | ND |
| 9/17/78 | | | 139 | 16 | 106 | 23 | 75 | 57 | ND | ND |
| 9/18/78 | | | 219 | - | 174 | - | 161 | - | ND | ND |
| 9/19/78 | | | 536 | 32 | 154 | 12 | 0 | 1 | ND | ND |
| 9/20/78 | | | 506 | 39 | 264 | 21 | 0 | 14 | ND | ND |
| 9/21/78 | | | 732 | 50 | 128 | 16 | 0 | 0 | ND | ND |
| 9/22/78 | | | 485 | 57 | 55 | 27 | 0 | 0 | ND | ND |
| 9/23/78 | | | 373 | 40 | 45 | 3 | 0 | 0 | ND | ND |
| wk. avg. | | | 427 | 39 | 133 | 17 | 34 | 12 | ND | ND |
| 11/19/78 | | | - | - | - | - | - | - | ND | ND |
| 11/20/78 | | | - | - | - | - | - | - | ND | ND |
| 11/21/78 | | | - | - | - | - | - | - | ND | ND |
| 11/22/78 | | | - | - | - | - | - | - | ND | ND |
| 11/23/78 | | | 180 | 49 | 229 | 71 | 479 | 197 | ND | ND |
| 11/24/78 | | | 187 | 32 | 241 | 44 | 465 | 112 | ND | ND |
| 11/25/78 | | | 169 | 50 | 220 | 75 | 474 | 195 | ND | ND |
| wk. avg. | | | 179 | 44 | 230 | 63 | 474 | 168 | ND | ND |

APPENDIX B

TABLE B-1. ALGAL SPECIATION FOR GRAB SAMPLES - March 9, 1978

| | Rock Filter Influent | | Rock Filter Effluent | |
|---|---|---|---|---|
| Taxon | genus-species | Rel. Abundance | genus-species | Rel. Abundance |
| Chlorophyta | Scenedesmus acuminatus | 0.195 | Scenedesmus acuminatus | 0.139 |
| | Chlorella vulgaris | 0.189 | Chlorella vulgaris | 0.458 |
| | Pyramimonas cf. tetrarhynchus | 0.166 | Ankistrodemus Falcatus | 0.125 |
| | Ankistrodesmus Falcatus | 0.112 | Chlamydomonas cf. globosa | 0.028 |
| | Chlamydomonas cf. globosa | 0.047 | Actinastrum hantzschii | 0.014 |
| | Coccomonas sp. | 0.30 | | |
| | Scenedesmus quadricauda | 0.006 | | |
| | Actinastrum hantzschii | 0.006 | | |
| Cyanophyta | Schizothrix calcicola | 0.018 | | |
| Euglenophyta | Astasia sp. | 0.016 | Euglena sp. 1 | 0.042 |
| | Euglena sp. 1 | 0.059 | Trachelomonas volvocina | 0.180 |
| | Euglena sp. 2 | 0.024 | Trachelomonas sp. 1 | 0.014 |
| | Trachelomonas volvocina | 0.012 | | |
| Pyrrhophyta | Glenodinium sp. | 0.030 | | |

TABLE B-2. ALGAL SPECIATION FOR GRAB SAMPLES - April 20, 1978

| | Rock Filter Influent | | Rock Filter Effluent | |
|---|---|---|---|---|
| Taxon | genus-species | Rel. Abundance | genus-species | Rel. Abundance |
| Chlorophyta | Chlamydomonas cf. globosa | 0.99 | Chlamydomonas cf. globosa | 0.44 |
| | Scenedesmus acuminatus | 0.01 | Scenedesmus acuminatus | 0.11 |
| | | | Chlorella vulgaris | 0.11 |
| | | | Actinastrum hantzschii | 0.06 |
| Euglenophyta | | | Euglena sp. 1 | 0.17 |
| | | | Trachelomonas sp. 1 | 0.11 |

TABLE B-3. ALGAL SPECIATION FOR GRAB SAMPLES - May 18, 1978

| | Rock Filter Influent | | Rock Filter Effluent | |
|---|---|---|---|---|
| Taxon | genus-species | Rel. Abundance | genus-species | Rel. Abundance |
| Chlorophyta | Tetraedron regulare | 0.75 | Tetraedron regulare | 0.83 |
| | Chlorella vulgaris | 0.05 | Scenedesmus acuminatus | 0.07 |
| | Scenedesmus acuminatus | 0.12 | Ankistrodesmus Falcatis | 0.07 |
| | Scenedesmus quadricauda | 0.04 | | |
| | Ankistrodesmus Falcatus | 0.01 | | |
| Chrysophyta | Nitzschia sp. | 0.02 | | |
| Pyrrhophyta | | | Gilenodinium sp. | 0.02 |

TABLE B-4. ALGAL SPECIATION FOR GRAB SAMPLES - August 2, 1978

| | Rock Filter Influent | | Rock Filter Effluent | |
|---|---|---|---|---|
| Taxon | genus-species | Rel. Abundance | genus-species | Rel. Abundance |
| Cyanophyta | Anacystis cyanea (Microcystis Flos-aquae) | 1.00 | Anacystis cyanea | 0.999 |
| | | | Schizothrix calcicola | 0.001 |

TABLE B-5. ALGAL SPECIATION FOR GRAB SAMPLES - September 21, 1978

| | Rock Filter Influent | | Rock Filter Effluent | |
|---|---|---|---|---|
| Phylum | genus-species | Rel. Abundance | genus-species | Rel. Abundance |
| Chlorophyta | Actinastrum hantzschii | 0.15 | Ankistrodesmus Falcatus | 0.01 |
| | Scenedesmus acuminatus | 0.10 | | |
| | Scenedesmus quadricauda | 0.02 | | |
| | Ankistrodesmus Falcatus | 0.02 | | |
| Cyanophyta | Anacystis cyanea | 0.70 | Anacystis cyanea | 0.99 |
| | Schizothrix calciola | 0.01 | | |

TABLE B-6. ALGAL SPECIATION FOR GRAB SAMPLES - November 24, 1978

| | Rock Filter Influent | | Rock Filter Effluent | |
|---|---|---|---|---|
| Phylum | genus-species | Rel. Abundance | genus-species | Rel. Abundance |
| Chlorophyta | Chlamydomonas cf. pertusa | 0.35 | Chlamydomonas cf. pertusa | 0.26 |
| | Chlorella vulgaris | 0.24 | Chlorella vulgaris | 0.09 |
| | Actinastrum hantzschii | 0.20 | Actinastrum hantzschii | 0.22 |
| | Scenedesmus acuminatus | 0.16 | Scenedesmus acuminatus | 0.26 |
| | Ankistrodesmus Falcatus | 0.02 | Ankistrodesmus Falcatus | 0.06 |
| | Scenedesmus quadricauda | 0.01 | Trachelomonas volvocina | 0.02 |
| Cyanophyta | | | Anacystis cyanea | 0.09 |